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THE UNIVERSITY OF ALBERTA

THE EFFECTS OF LONGTERM MANAGEMENT ON SOIL CHEMICAL AND PHYSICAL PROPERTIES.

by

SHIRLEY J. LUTWICK

(C)

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

IN

SOIL MANAGEMENT

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

SPRING, 1989

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled THE EFFECTS OF LONGTERM MANAGEMENT ON SOIL CHEMICAL AND PHYSICAL PROPERTIES, submitted by SHIRLEY J. LUTWICK in partial fulfillment of the requirements for the degree of Master of Science in Soil Management.

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The Effects of Long-Term Cultivation on Soil Physical and Chemical Properties

ABSTRACT

Some areas of the Canadian prairies are approaching 100 years of cultivation. The land was broken, then tillage and yearly cropping was carried out. Management practices such as the application of commercial fertilizer, addition of manure, and irrigation became commonplace.

After 75 to 100 years, concerns are mounting regarding the effects of continuous cultivation on soil properties. There are concerns regarding degradation of soil structure and increased susceptibility to erosion, depletion of nutrients, and accumulations of potentially toxic elements.

The Rotation U plots in Lethbridge were established in 1911 as a series of one-acre plots undergoing a 10-year crop rotation. The plots have now been maintained for 75 years. Samples were taken from these plots every 10 years since 1911. Portions of these samples were analyzed to provide information on soil physical and chemical properties.

The data of this study showed there were sporadic changes in some soil chemical properties. The aggregate stability of the plot soils has declined marginally. The clay content has increased with time. The changes in these two parameters suggest that some structural deterioration has taken place.

The analyses indicate that total K content has declined and total Ca has increased markedly since the breaking of the plots. The levels of soluble and exchangeable Na, K, and Mg have fluctuated over 75 years while soluble and exchangeable Ca showed strong initial increases but has declined over recent decades. The levels of trace elements have fluctuated very little in seven decades. While no accumulations of potentially toxic elements were noted, neither is there any evidence of micronutrient deficiencies.

Contents of organic matter, total N, total P, and total S have been maintained over the life of the plot. The cation exchange capacity has remained fairly constant for 73 years. These results are in contrast to reports of other rotations (grain, grain-fallow) on similar soils. The indication of the relatively low amount of physical degradation and the maintenance of organic matter and N, P, and S levels is considered to be a result of the management program which includes six years of alfalfa as part of the 10-year cropping sequence, and the addition of fertilizer and manure. The amount and frequency of fertilizer and manure applications on Rotation U appear to be environmentally sound while permitting excellent crop yields and maintenance of soil nutrient levels.

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TABLE OF CONTENTS

CHAPTER		Page
	Abstract	iv
	Acknowledgements	vi
I.	Introduction	1
	Rotation U Plots: History	2
II.	Literature Review	10
III.	Materials and Methods	52
	A. Physical Properties	
	1. Aggregate Stability and Particle Size by Dispersion	53
	2. Particle Size Analysis by Hydrometer	54
	3. Dry Sieving	54
	4. Wet Sieving	54
	5. Micromorphology	55
	B. Chemical Properties:	
	1. Total N and P	55
	2. Total K	56
	3. Total S	56
	4. Soluble Salts	56
	5. Exchangeable Cations	57
	6. Total Cation Exchange Capacity	57
	7. CaCO3	58
	8. Total Carbon	58
	9. Trace Elements	58
IV.	Results and Discussion	
	A. Physical Properties:	
	1. Particle Size Analysis:	
	1.1 Dispersion	59
	1.2 Hydrometer	63
	2. Water Stable Structure:	
	2.1 Water Dispersible Clay	66
	2.2 Wet Sieving	71
	2.3 Dry Sieving	73
	3. Micromorphology:	73

TABLE OF CONTENTS

CHAPTER		Page
	B. Chemical Properties	
	1. Total Carbon and Organic Matter	76
	2. CaCO3	83
	3. Total N	87
	4. Total P	92
	5. Total K	95
	6. Total S	99
	7. Total Calcium and Magnesium.....	103
	8. Soluble Salts	108
	9. Exchangeable Cations	108
	10. Total Cation Exchange Capacity	112
	11. Trace Elements	115
V.	CONCLUSIONS	139
	BIBLIOGRAPHY	141
	APPENDIX	149

LIST OF TABLES

Table	Description	Page
1.	Sampling dates, management changes, soil amendments and time of application to plot 5 of Rotation U.	3
2.	Crop rotation scheme of Rotation U plots (after 1951 revision).	7
3.	Loss of total N from cultivated soils in Western Canada.	16
4.	Loss of organic matter from cultivated soils in Western Canada.	18
5.	Content of sand, silt and clay of plot 5 compared to control site in 1985.	65
6.	Results of wet and dry sieving analyses of bulk samples taken from plot 5 and control site in 1985.	72
7.	Content of inorganic carbon (%) of plot 5 soils from 1911 to 1984.	78
8.	Content of organic matter (%) of plot 5 soils 1911 to 1984.	78
9.	Content of total Mg (%) of Rotation U Plot 5 soils from 1911 to 1984.	107
10.	Content of soluble salts (ug/g) in Rotation U Plot 5 soils from 1911 to 1984.	109
11.	Content of exchangeable cations (cmol/kg) in Rotation U Plot 5 soils from 1911 to 1984.	110
12.	Elements in soil samples which occurred at or below INAA detection limits.	116
13.	Content of elements in soils which appeared unchanged during the history of plot 5.	116
14.	Elemental content of two fertilizers used in Rotation U plots.	117

LIST OF FIGURES

Figure		Page
1.	1971 Plan for Rotation "U."	8
2.	Content of sand, silt, and clay in 0 - 15 cm depth of Rotation U Plot 5 from 1911 to 1984.	60
3.	Content of sand, silt, and clay in 15 - 30 cm depth of Rotation U Plot 5 from 1911 to 1984.	61
4.	Content of water dispersible clay in 0 - 15 cm depth of Rotation U Plot 5 from 1911 to 1984.	67
5.	Content of water dispersible clay in 15 - 30 cm depth of Rotation U Plot 5 from 1911 to 1984.	68
6.	Content of total carbon in 0 - 15 cm depth of Rotation U Plot 5 from 1911 to 1984.	79
7.	Content of total carbon in 15 - 30 cm depth of Rotation U Plot 5 from 1911 to 1984.	80
8.	Content of CaCO3 in 0 - 15 cm depth of Rotation U Plot 5 from 1911 to 1984.	84
9.	Content of CaCO3 in 15 - 30 cm depth of Rotation U Plot 5 from 1911 to 1984.	85
10.	Content of total N in 0 - 15 cm depth of Rotation U Plot 5 from 1911 to 1984.	88
11.	Content of total N in 15 - 30 cm depth of Rotation U Plot 5 from 1911 to 1984.	89
12.	Content of total P in 0 - 15 cm depth of Rotation U Plot 5 from 1911 to 1984.	93
13.	Content of total P in 15 - 30 cm depth of Rotation U Plot 5 from 1911 to 1984.	94
14.	Content of total K in 0 - 15 cm depth of Rotation U Plot 5 from 1911 to 1984.	96
15.	Content of total K in 15 - 30 cm depth of Rotation U Plot 5 from 1911 to 1984.	97
16.	Content of total S in 0 - 15 cm depth of Rotation U Plot 5 from 1911 to 1984.	100
17.	Content of total S in 15 - 30 cm depth of Rotation U Plot 5 from 1911 to 1984.	101

18. Content of total Ca in 0 - 15 cm depth of Rotation U Plot 5 from 1911 to 1984. 104

19. Content of total Ca in 15 - 30 cm depth of Rotation U Plot 5 from 1911 to 1984. 105

20. Total cation exchange capacity of 0 - 15 cm depth of Rotation U Plot 5 from 1911 to 1984. 113

21. Total cation exchange capacity of 15 - 30 cm depth of Rotation U Plot 5 from 1911 to 1984. 114

LIST OF PLATES

Plate	Description	Page
1.	Micrograph of control site (3x magnification).	74
2.	Micrograph of A p horizon of Plot 5 showing fragments of Bm admixed with A (3x magnification).	75
3.	Micrograph of A p horizon of Plot 5 showing compacted structure (3x magnification).	75

INTRODUCTION

The Chernozemic soils of the Canadian prairies developed under a grassland ecosystem. In their native state, these soils had a high cation exchange capacity, which was dominated by calcium and magnesium, and had a high content of organic matter. When first cultivated, the physical condition of these soils was near optimum for ease of root penetration and maximum resistance to wind and water erosion, had good air-water relationships at field capacity, and allowed preparation of good seedbeds. Tillage and cropping changed the physical structure of the soil. These desirable properties began to depreciate, although the rate of deterioration varied with the system of management, soil type, and climatic conditions.

Prairie Chernozems have now been cultivated for 75 to 100 years, and concerns are increasing in regard to the effects of continuous cultivation on soil properties. The results of tillage, cropping, manure and commercial fertilizer application, residue incorporation, and irrigation techniques are being monitored.

The degradation of soil structure and subsequently heightened susceptibility to erosion and reduced resistance to wetting and mechanical impact by rainfall is one area of concern. The size and arrangement of particles and pores determine whether a favorable plant root environment exists. Deterioration of the soil structure of these Chernozems makes physical conditions less favorable for plant growth.

Along with physical degradation, cultivation often results in depletion of organic matter content, changes in the quality of organic matter and the subsequent reduction of nutrient availability. Depletion of N, P, K, and S with cultivation is commonly reported.

The reversibility of these trends is a major area of concern. Levels of micronutrients and other trace elements are currently of special interest. In order to evaluate the effects of tillage, cropping, fertilizer, manure, and irrigation treatment, the normal ranges of concentration for each trace element in the soil must be established. Background information on trace elements would allow assessment of potential deficiencies of micronutrients. Information about baseline levels of trace elements can also be used to determine whether pollution has been caused by industrial waste products, application of sewage sludge, fall-out from automobile exhaust, and residual effects of fertilizer or manure amendments, and applications of herbicides and pesticides.

Rotation U Plots: History

The Rotation U plots are located on the Agriculture Canada Research Station at Lethbridge, Alberta, Canada. The soil is classified as an Orthic Dark Brown Chernozem (Lethbridge Series) developed on alluvial lacustrine parent material. The texture of the surface 30 cm is generally loam. Rotation U was broken from virgin sod in 1907. It was seeded to grain for three years, 1908 to 1910. The plot

Table 1. Sampling dates, management changes, soil amendments and time of application to Plot 5 of Rotation U.

Sampling date	Management Changes	Fertilizer application*	Manure application**
1911			
1922	1923 Sugarbeets replace potatoes		1919
1933	1933 Fertilization began (0-43-0)		1929
		1935	
	1938 Switched to (11-48-0)	1938	1939
1941			
		1942	1944
		1945	
			1946
		1948	
	1951 Plot 1 moved		1950
1951	1951 6 yrs alfalfa split 2 x 3 yr		
		1953	
		1955	
	1959 Vernal sub. for Grimm Alfalfa		1956
		1960	
1961			
			1962
		1963	
		1965	
			1966
	1967 Switch to sprinkler irrigation	1970	
1971	1971 Sugarbeet, wheat position switched; Alfalfa seeded without nurse crop		
			1972
		1974	
		1975	
		1980	1977
1981			
			1982
1984		1984	

*110 kg/ha; 1933-1937 - 0-43-0; 1938-1984 - 11-48-0.

**1911-1942 - 27 t/ha.; 1942-1984 - 33.5 t/ha.

system was established in 1911 as ten 0.4-ha plots. The rotation became fully established with the completion of the first cycle of rotation in 1920. The first ten years of existence of the plots showed that extremely high yields could be attained under irrigation. (Dubetz, 1983).

The original crop sequence of the ten-year rotation consisted of six years of alfalfa, then one year each of potatoes, wheat, oats, and barley. Alfalfa was a major cash crop at the time. Alfalfa hay was required for the many horses and mules used in the construction of irrigation works and railroads. Twenty-seven t/ha of manure were applied in the fall to the 0.4-ha plot growing the fifth year of alfalfa. In 1923, sugarbeets were substituted for potatoes, becoming the only crop change in the history of the plots. Sugarbeet tops are returned to the land, while cereal crop straw is hauled away.

Midway through the second decade alfalfa yields began a decline which continued into the third rotation cycle. Phosphorus deficiency was thought to be the cause, and in 1933 the plots were split lengthwise and 110 kg/ha of triple superphosphate (0-43-0) was applied to the south half of each of three plots: first-year alfalfa, fourth-year alfalfa, and sugarbeets. The benefits of fertilization became rapidly apparent in the higher yields of alfalfa and sugarbeets. In 1938, ammonium phosphate (11-48-0) was substituted when the manufacture of triple superphosphate was discontinued in Canada. The manure application was

increased from 27 t/ha to 67 t/ha in 1942. The application was split, with 33.5 tonnes each being applied to the plots growing the second-year alfalfa and the sixth year of alfalfa. Over 10 years, each 0.4-ha plot received 67 tonnes of manure. This rate of manure application was intended to replace the nutrients, particularly N and P, removed by the crops, especially in the unfertilized north halves of the plots. (Dubetz, 1983)

The early 1940's saw a severe decline in alfalfa yields as a result of alfalfa wilt and crown bud rot. Alfalfa stem nematode was also a concern. Some plots produced yields of less than two t/ha. To boost alfalfa yields, a major cropping change was introduced in 1951 (shown in Table 2). The six years of alfalfa were split into two three-year plantings, separated by barley and oats, or by wheat and sugarbeets. In 1951, the construction of Highway 3 encroached upon the plot configuration (Figure 1). The topsoil of Plot 1 was excavated and shifted to a cleared location immediately south of Plot 10. The highway right-of-way has cut off a portion of the northwest corner of Plot 2. In this way, the rotation was continued with the minimum possible disturbance. In 1959, the alfalfa cultivar Vernal, which showed some resistance to bacterial wilt, was substituted for the susceptible Grimm. A final change in cropping sequence was made in 1971 when the positions of wheat and sugarbeets were switched to allow early cultivation of beets without interference from remaining

alfalfa roots. Also, since 1971, alfalfa has been seeded without a companion crop. One cut is now taken from new alfalfa plots and two cuts per year from the established plots. The alfalfa cultivar Trek, highly resistant to bacterial wilt and alfalfa stem nematode, has been used since 1974.

Irrigation was applied to all plots to maintain soil water in the upper half of the available range. From 1911 to 1966, surface irrigation of 10-15 cm of water was applied as required, depending on crop type and amount of precipitation. Sprinkler irrigation was introduced in 1967. The newer system supplies smaller and more uniform applications of water (Dubetz, 1983). The change in irrigation technique has resulted in the dropping of the water table in the area of the plots. Originally, the water table was within 1.5 metres of the surface, and is now considerably deeper. Drainage has improved, and water table fluctuations no longer affect upper horizons as severely.

Under the collective heading of cultivation, the combined effects of tillage, cropping, fertilizer application, manure addition, residue incorporation, and irrigation were considered. The specific objectives of this study were:

1. To study the effects of cultivation since 1911 on the chemistry of the soil. Changes in content of macronutrients N, P, K and S were studied along with the levels of soluble salts, exchangeable cations, cations exchange capacity, content of $CaCO_3$, and content of

Table 2. Crop rotation scheme of Rotation U plots (after 1951 revision).

Crop	Treatment
Wheat and alfalfa	None
Alfalfa 1a	11-48-0 @ 110 kg/ha to south half
Alfalfa 2a	Manure @ 33.5 t/ha
Alfalfa 3a	None
Barley	None
Oats and alfalfa	None
Alfalfa 1	11-48-0 @ 110 kg/ha to south half
Alfalfa 2	None
Alfalfa 3	Manure at 33.5 t/ha
Sugarbeets	11-48-0 @ 110 kg/ha to south half

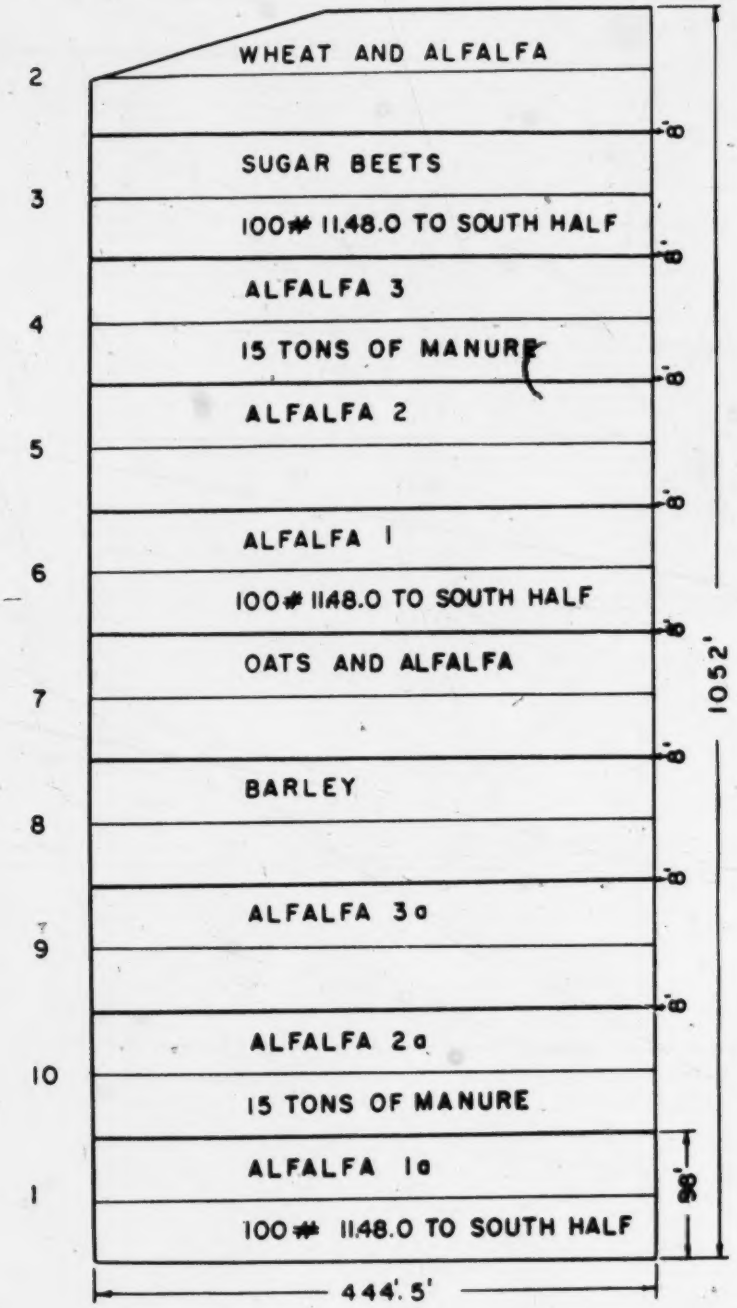

Figure 1. 1971 Plan for Rotation "U".

carbon. In addition, the levels of micronutrients and other trace elements were included in this assessment. For many trace elements, there is little information regarding their normal concentrations in Prairie Chernozems. This study established their background levels and permitted study of concentration alterations since the 1911 breaking of the grassland to the present. This information on the status of trace elements in this soil will allow assessment of future pollution of the plot and trace element utilization and cycling.

2. To study the effects of cultivation on aggregate stability, particle size distribution, and micromorphological features.

LITERATURE REVIEW

Physical Properties

When grassland is initially cultivated, the physical condition of the soil is nearly optimum for the preparation of good seedbeds over a wide range of moisture contents. At field capacity, the air-water relationships are good for plant growth, there is maximum resistance to wind and water erosion, and roots are easily able to penetrate the soil. As soil is cultivated, these desirable properties begin to deteriorate although the rate of deterioration varies with the system of management and soil type (Low, 1972). References to breakdown of soil structure on ploughing are numerous, particularly in the US, USSR, and Canada.

The size and arrangement of soil particles and pores constitute soil structure. The pores store water which is then available for use by plants. Pores allow transmission of air and water, and permits root growth (Oades, 1984). Root development is greater and yields are higher on soils with many visible pores (Low, 1972). Soil structure is dynamic and is capable of changing in response to alterations in natural conditions, biological activity, and soil management practices. Since soil structure so greatly affects the water, air and heat regimes of the soil system, it is of major importance in determining soil productivity. Soil structure determines the mechanical properties of the soil which, in turn, affect seed germination, seedling establishment, and the growth of roots. These influences of

soil structure can affect the performance of various agricultural operations including seeding, tilling, irrigation, and drainage (Hillel, 1971). Soil structure is not measurable, therefore to quantify changes in soil structure various aspects of changes in soil physical properties are analyzed (Low, 1972).

In a single-grained soil structure, particles are completely unattached. In a massive structure, the particles are bonded together in large blocks. An aggregated soil consists of particles organized in small peds held together by intra-aggregate bonds. This aggregated structure can be described qualitatively by noting aggregate shapes or quantitatively by measuring aggregate sizes. This can be accomplished by the use of wet and/or dry sieving techniques. Wet sieving is also used as an index of the stability of the aggregates to slaking by water (Hillel, 1971). Wet sieving relies on a direct measurement of a change in particle size distribution (Williams et al., 1966).

The best soil structural arrangement should be resistant to disruption upon wetting or slaking. The slaking action produces micro-aggregates from which clay may disperse. Where dispersible clay is present, porosity is decreased and bulk density increases, soil strength increases, infiltration rate of water decreases, hydraulic conductivity is reduced, and unfavorable physical conditions for crop growth result (Oades, 1984; Dormaar and Pittman,

1980). Additional methods of characterizing soil structure include measurements based on the size distribution of the pores, permeability to air and water, or physical properties such as bulk density, water-holding capacity, modulus of rupture, and aggregate stability.

Intensive tillage is a common farming practice. Tillage prepares a proper seedbed, promotes infiltration and storage of water, incorporates herbicides and fertilizers, controls weeds, and spreads and incorporates residue. All tillage treatments increase the fraction of fine soil aggregates while decreasing the portion of larger aggregates (Nuttall et al., 1985). Reduction of pore space by machinery can be considerable (Low, 1972). With the percentage increase of smaller aggregates, the possibility of erosion increases. Grieve (1980) noted that aggregate stability of cultivated soils is considerably less than that of grassland and that under cereal cultivation there is a serious reduction in soil structure resistance to deformation, particularly to the wetting and mechanical impact of rainfall. Low (1972) found that the number of water stable aggregates fell very sharply in the first few years that a grassland was cultivated and then declined more slowly. Fallowing was the poorest management treatment with respect to soil structure maintenance. Fallow fields contain the lowest proportion of water stable aggregates when compared to similar fields cropped with wheat (Dormaar and Pittman, 1980; Oades, 1984). It was suggested by Nuttall et al. (1985) that lack of crop

residue cover could possibly cause lower winter soil temperatures that promote reduction in aggregate size.

Formation and stability of soil aggregates depends to a large extent on the quantity and condition of clay and upon the presence of various forms of organic matter (Hillel, 1971). Flocculation of soil clay is necessary for aggregate formation. Greenland (1965), suggested that, in addition to stabilizing aggregates by providing a hydrophobic coating to some pores, long chain organic polyanions flocculate clays by forming inter-particle bonds or "cation bridges". Consequently, the presence of organic matter permits existence of individual aggregates exhibiting mechanical strength.

Although there is a general relationship between water stable aggregation and carbon content, the correlation is weak because total organic carbon may not be correlated with the carbon content of those organic compounds which influence the physical properties of soil. Also soil aggregates can be stabilized by aluminum and iron oxides and calcium carbonate as well as by humic materials and undecomposed organic matter (Greenland, 1965; Hillel, 1971). Root systems stabilize aggregates because of a high production of mucilages and polysaccharides. Grasses in particular are considered to be efficient "structural improvers" because they maintain a large pool of mucilages and polysaccharides (Oades, 1984). The roots and associated hyphae do not persist in soil for much more than a year.

Annual replacement of root systems is required or the binding effects disappear and the number of aggregates declines. It has been noted that increased frequency of fallowing causes a more rapid reduction of soil organic matter levels (Dormaar and Pittman, 1980). When roots and hyphae decompose the fragments can become centers of aggregates. The mucilages interact with clay and encrust the organic matter, thereby slowing its decomposition. The resulting aggregates are bound by a matrix of humic materials and mucilages and are very stable until severe chemical or physical stress initiates clay dispersion. Even under chemical conditions promoting aggregate stability, the aggregates are vulnerable to physical disturbances. The effects of water can break down aggregates. The swelling and shrinking of clays under wetting and drying cycles are disruptive to aggregates as is ice formation, raindrop action, and the scouring effect of runoff water. Excessive tillage and compaction promotes aggregate destruction. The soil surface is particularly exposed to physical disruption by tillage, rain, and compaction by traffic. The result can be an impervious surface crust which impedes infiltration of water and gas exchange and inhibits emergence of seedlings (Hillel, 1971). Optimal crop growth while maintaining desirable soil structure requires proper soil management techniques coupled with appropriate cropping rotations.

In summary, soil initially broken from grassland is in nearly optimal condition for crop growth. The soil shows

desirable physical structure and adequate amounts of all elements necessary for plant nutrition. Under cultivation, the desirable soil structural properties are reported to deteriorate, and macronutrient contents (N,P,K,S) begin to decline. There is also a reported decline in organic matter, accompanied by chemical alteration of the remaining organic matter. The net result is a decline in productivity. The deleterious effects of cultivation can apparently be avoided or reversed by use of appropriate soil management techniques which may include fertilization, organic matter additions through manure applications and crop residue incorporation, and crop rotations particularly those involving legumes or grass.

Chemical Properties

Generally, the effect of long-term cultivation on the soils of the Canadian Prairies has been a decline of total N, P, K, S, and C (Table 3).

Total Nitrogen

Total N losses are of major concern. Upon cultivation and cropping with small grains, soils of Saskatchewan have been observed to lose 1% of their total N per year for 20-30 years (Tiessen et al., 1982). Upon initial cultivation, southern Alberta soils were found to contain more than adequate amounts of available nutrients. By the early 1920's, there were already reports of N losses (Shutt, 1925).

Table 3. Loss of total N from cultivated soils in Western Canada.

Relative loss of total N (%)	Cultivation time (yr)	Soil *	Reference
22	25	Dk.B	Caldwell, 1939
37	26	Dk.B.Ch.	Newton, 1945
25	46		Hill, 1954
75	20		Low, 1972
49	60	B.Ch.	Martel and Paul, 1974
60	65	Ch.	Dormaar, 1979
46		Dk.B.Ch.	Dormaar and Pittman, 1980
49	50-70	Bl.Ch.	Bettany et al., 1980
34	60-70	O.Bl.Ch.	Tiessen et al., 1982
18	60-70	Dk.B.Ch.	Tiessen et al., 1982
46	60-70	Dk.B.Ch.	Tiessen et al., 1982

* Dk. B. (Dark Brown), Dk. B. Ch. (Dark Brown Chernozem), B.Ch. (Brown Chernozem), Ch. (Chernozem), Bl. Ch. (Black Chernozem), O.Bl.Ch. (Orthic Black Chernozem).

Total Phosphorus

Concomitant declines in P levels were also soon noted (Shutt, 1925). The annual loss of total P was estimated by Tiessen, Stewart, and Bettany (1982) to be approximately 0.3% per year. Spratt and McCurdy (1966) suggested that frequently the organic P fraction accounts for all losses.

Manure at 27 t/ha every 4 years increased P (Dubetz et al., 1975). Pittman (1977) stated that 20 years of cropping reduced available P but not total P. Hill (1951) stated that P status can be maintained or enhanced with crop rotation and the addition of minimal fertilizer and manure.

Organic Matter

A decrease in organic matter results in a reduced capacity for nutrient supply. Soils under cultivation for small grain production lost 1% of their organic carbon per year during the first 20-30 years (Tiessen et al., 1982). Organic matter losses of 50 to 66% over periods of 20 to 40 years of cultivation were reported by Skjemstad et al (1986). The soils under study were Typic Chromustert clay soils, dark greyish brown to dark brown in color which were alkaline at the surface and acid at depth. These soils are used primarily for wheat production in Queensland, Australia. The rate of organic matter loss diminishes with time. It has been suggested that the organic matter net loss will eventually cease when the soil has reached an equilibrium for the crop rotation and cultivation scheme. Cessation of organic matter loss after 22 years was proposed

Table 4. Loss of organic matter from cultivated soils in Western Canada.

Loss of OM (%)	Cultivation time	Soils *	Reference
26	25	Dk. B.	Caldwell, 1939
39	26	Dk. B. Ch	Newton, 1945
18	46	Dk. B. Ch	Hill, 1954
49	60	B. Ch.	Martel and Paul, 1974
60	65	Ch	Dormaar, 1979
46		Dk. B. Ch	Dormaar and Pittman, 1980
49	50-70	Bl. Ch.	Bettany et al., 1980
32	60-70	O. Bl. Ch.	Tiessen et al., 1982
37	60-70	O. Dk. B. Ch	Tiessen et al., 1982
46	60-70	Dk. B. Ch.	Tiessen et al., 1982

* Dk.B. (Dark Brown), Dk.B.Ch. (Dark Brown Chernozem), B.Ch. (Brown Chernozem), Ch. (Chernozem), Bl.Ch. (Black Chernozem) O.Bl.Ch. (Orthic Bl.Chernozem), O.Dk.B.Ch. (Orthic Dk. Brown Chernozem).

by Shutt (1925) while Martel and Paul (1974) suggested a period of 60-70 years was required, based on radiocarbon dating of Prairie soils. Tiessen et al. (1982) concluded that soil organic matter losses do not level off. The continued decline is caused by increased loss due to erosion as a result of lowered organic matter content and by an extension of the zone of organic matter depletion into lower soil horizons.

Cultivation also causes changes in the chemical structure of the remaining organic matter. Generally, the proportion of side chain components such as C-H and NH_2 groups increased. The humic materials then have a higher proportion of aromatic components and, therefore, have increased association with the clay fraction (Dormaar, 1979). Skjemstad et al (1986) concluded that persistent organic matter is relatively stable because of an association with soil inorganic components. Changes in organic matter characteristics have also been noted by Dubetz et al. (1975). McLaren and Swift (1977) found that cropping and cultivation caused a decrease in total organic sulphur contents.

Management can significantly alter the rate of organic matter decline. Increased frequency of fallowing causes a more rapid loss of organic matter (Dormaar, 1979). This consequence of fallowing on change in organic matter levels has often been reported. Pittman (1977) reported losses of 12% of the organic matter following 20 years of continuous

wheat culture while 17% of organic matter was lost from a wheat-fallow rotation over a 20 year period and 19% of the organic matter was lost from a wheat-wheat-fallow rotation system during the same 20-year period. The soil was a Dark Brown Chernozem which originally contained 2.87% organic matter. According to Odell (1984), crop rotations retard loss of soil organic matter compared to losses noted under monoculture. To maintain organic matter at its highest levels, crop rotations including legumes or legume-grass plus fertilization have been used. The beneficial effects of legumes in crop rotations in slowing organic matter loss was also indicated by Pittman (1977), who also described the benefits of manure application in maintaining organic matter levels. Soil amendments affect the chemical characteristics of organic matter. Levels of extractable C increase, the C content of humic substances rises, and there is also an increase in the C:N ratio (Dubetz et al., 1975). Dormaar and Pittman (1979) noted that cultivated soil contained 100% more solvent extractable C and 49% more resin extractable C than proximate native grassland.

Generally, researchers agree that cultivation decreases the organic matter content of soil and that in this process the chemical structure of remaining organic matter is altered. The rate of organic matter loss is retarded or reversed by inclusion of legumes in the crop rotation, the elimination of fallowing, application of manure and appropriate chemical fertilizers and incorporation of crop residues.

Management techniques can have a profound effect on of soil quality and fertility. Proper management can improve organic matter levels in a poor soil or in a soil from which organic matter has previously been lost. These management practices can be used for maintenance of organic matter, improvement of organic matter levels, and reclamation of mismanaged soils.

Potassium

Years of cropping have to reduced exchangeable K levels on Dark Brown Chernozemic soils (Pittman, 1977). The loss of K may be partially due to the inclusion of alfalfa in the rotation scheme of Rotation U. Alfalfa removes large amounts of K from the soil. Loss of exchangeable K (as well as other elements)can be reversed by the application of manure. Dubetz et al. (1975) noted that the application of 27 t/ha of manure every 4 years increased the K levels of the soil.

In 1912, a series of dryland crop rotations were established at the Lethbridge Research Station on Dark Brown Chernozemic soil. The rotations included:

1. continuous wheat
2. alternate wheat and fallow
3. wheat - wheat - fallow
4. fallow - wheat - oats - fallow - peas and oats - oats
5. fallow - corn - winter rye - fallow - oats - wheat - fallow- peas and oats - wheat

6. fallow - winter wheat - alfalfa - alfalfa - alfalfa - fallow - corn - wheat

After forty years, Hill (1954) found no differences in K content of soils under the various rotations.

In the province of Alberta, differences in soil levels of exchangeable K are related to the nature of the K-bearing soil minerals, soil texture and pedogenesis. Deficiency of K is largely restricted to coarse textured Black, Luvisolic, and organic soils.

The Brown and Dark Brown soils of southern Alberta are plentifully supplied with K. Halstead and Nyborg (1970) in their investigation of response to K fertilizer found that the average yield without K fertilizer was 101% of that with fertilizer treatment in the Brown and Dark Brown soil zones. These arid and semi-arid regions are high in K possibly because very little K is lost through leaching (Dubetz and Dudas, 1981). Although responses to K fertilizer are seldom obtained, it is likely that K deficiency will eventually occur. The intensively cropped irrigated soils of southern Alberta would probably demonstrate deficiency levels of K before similar dryland areas.

The surface soils of Brown Chernozems are higher in exchangeable K than those at depth. This situation is enhanced by the action of native plants which utilize K from lower depths and return it to the surface on mineralization.

Sulphur

According to McLaren and Swift (1977) the predominant

form of sulphur in the soil is the organically bound fraction. Inorganic forms make up only a small portion of the total sulphur content. In order for organic sulphur to become available to plants, it must first be mineralized to sulphate. As sulphur inputs to the soil system through fertilizer additions and atmospheric depositions decrease, this process of mineralization becomes important in maintaining sulphur availability to plants.

Mineralization of organic sulphur in soil cultivated for many years results in differences in the distribution, nature, and amounts of sulphur compared to that of similar uncultivated or pasture soils. The research of McLaren and Swift (1977) shows that the total organic sulphur contents of a pasture were higher than that of cultivated soils. The cropping process caused loss of S during the mineralization of an organic matter. Additions of sulphur as fertilizer or manure produce short-term fluctuations only in the organic S levels. In the uncultivated soil C:S ratios were higher than was the case for cultivated soil, indicating that S mineralizes more slowly than C.

Generally, the total S of the soil organic matter is decreased by long-term cultivation. Chernozems losing more than 50% of organic S in 50-70 years of cultivation were reported by Bettany et al. (1980). Sulphur deficiency is becoming more commonly reported in Chernozemic soils while deficiencies were once mainly confined to leached Luvisols.

Bettany et al. (1980) reported a cultivated Black

Chernozem which contained 38% less S than permanent pasture while also containing 44% less C and 49% less N. This again suggests that S is more resistant to mineralization than either C or N and reinforces the theory that S is not analogous to C and/or N in humic transformations.

Calcium and Magnesium

Calcium is the fifth most abundant element in the earth's crust, averaging 3.6%. The total Ca content in the soil depends mainly on parent material and degree of weathering (Barber, 1984). Calcium is a divalent alkaline earth cation. Calcium is present in minerals with varying degrees of solubility, as exchangeable cations associated with soil colloids, and in smaller amounts in soil solution where Ca ions are balanced by soluble anions. The solution and exchangeable Ca are the plant available forms (Barber, 1984).

The most soluble of the soil Ca minerals are $CaSO_4 .2H_2O$ (gypsum) and $CaCO_3$. Gypsum is present in arid soils where $SO_4^=$ in solution is greater than 0.01 me/l (Barber, 1984). Calcium carbonate is present only in soils with pH values greater than 7. In soils above pH 8, $CaCO_3$ is the main control on the Ca levels in solution.

In many soils Ca is the dominant exchangeable cation. The exceptions are alkaline soils containing very high amounts of Na, acid soils with high contents of Al and H and serpentine-derived soils with a very high proportion of Mg. Soil solution Ca and exchangeable Ca are in an equilibrium

which is governed by the strength of the bonding to the exchange site. The anions and complementary cations present, the degree of Ca-saturation of exchange sites and the nature of the exchange sites affect bonding. Calcium is bonded more tightly than Sr to organic exchange sites while Sr is more tightly bound to permanent charge sites on clay (Juo & Barber, 1969). The field strength of organic sites is high enough that cation adsorption is determined by unhydrated cation radius. The permanent charge sites of clays have lower field strength so order of cation absorption is related to hydrated ion size, with the larger cation held more weakly (Juo & Barber, 1969). Exchangeable Ca is always held tighter than K or Mg.

The concentration of Ca in solution is affected by many factors: CO_3^{2-} concentration, which in turn controls carbonate and bicarbonates, equilibria level of anions in solution, bonding strengths of exchangeable cations, complementary cations, and degree of Ca saturation of exchange sites (Barber, 1984).

Magnesium is the eighth most abundant element in the earth's crust at 2.1% (Barber, 1984). Many soil minerals such as dolomite and olivine contain Mg. Magnesium is present in clays including montmorillonite, vermiculite, and chlorite. Total soil Mg can range from 0.015 - 1.02% (Barber, 1984). Total Mg usually increases with increasing clay contents.

The soluble and exchangeable forms of Mg are plant

available. In soils with pH values greater than 5.5, more than 60% of the exchangeable cations are Ca plus Mg. Remaining exchange sites are most commonly occupied by K, Na, Al, and H (Barber, 1984). Soil solution Mg is in equilibrium with exchangeable Mg.

Trace Elements

The occurrence and behavior of trace elements in soil are now topics of increasing interest as concern about the quality of the natural environment grows. High levels of Hg were discovered in fish of Japan and North America and were related to industrial contamination of the ecosystems. As a result of these findings, attention was drawn to other potentially hazardous elements such as As, Se, Cr, Sb, Ba, and Zn and others which are ubiquitous in the terrestrial environment. There are fears that contributions of these elements from various sources will result in accumulations of toxic levels of elements in soil and water where they could move through the food chain with negative effects on crops, livestock, other animals, and humans. Conversely, since some trace elements (notably Fe, Mn, Zn, Cu, Co, Mo, B, and Cl) are known to be required for plant nutrition, there is concern that environmental alterations such as cultivation and cropping could produce deficiency levels of these micronutrients in the soil, leading to further deficiency levels in plants grown on the deficient soil and in animals feeding on those plants.

Trace metals and water soluble organic substances can form fairly stable organo-metallic compounds (Blaser, 1950). Dissolved organic substances are capable of:

1) complexing metals and increasing metal solubility
2) altering distribution between oxidized and reduced forms of metals
3) influencing extent of adsorption on suspended matter
4) affecting stability of metal-containing colloids.

These actions all influence trace metal availability and, therefore, alter the prospects of deficiency or toxicity.

Trace elements are contributed to the soil from many sources. The major source is the mineral material from which the soil was formed. In addition to the mineralogical composition of the parent material, the total content of each trace element depends on intensity and type of weathering, and on climatic and other factors during pedogenesis. Rock and mineral stability and therefore their resistance to weathering are major factors in determining the texture and the trace element content of soils. The finer fractions of soils are most likely to have been produced from the more easily weathered minerals, which are the main suppliers of trace elements. Coarser fractions are derived from more resistant minerals such as quartz, which have low trace element contents (Hodgson, 1963).

Under normal agricultural practices trace elements are also added as impurities in fertilizer and lime, in manure, and in pesticide applications. From the atmosphere trace

elements are contributed by the settling or raining out of wind-eroded soil particles, industrial debris, fossil fuel combustion products, nuclear fallout, pollen, meteoric or volcanic dusts, and other air-borne particles. Trace metals can also be added to soil systems on soil particles displaced by water erosion or as metals dissolved or suspended in water (Lisk, 1972; Forstner and Wittman, 1979).

Even in a seriously deficient soil, the total amounts of micronutrients are generally in excess of crop requirements. These elements may not be available to plants, however, because they are tied up as constituents of minerals, or bound by iron or manganese oxides, or specifically adsorbed by soil solids such as clay minerals and organic matter. The availability of trace elements will depend on factors affecting these binding processes, including pH, redox potential, soil texture, mineral composition, amount and type of organic compounds, competitive interactions between elements, soil temperature and moisture, and microbiological activity. For example, if the pH is high enough or the salt concentration is high enough, metal ions will be desorbed from exchange sites (Ellis and Knezeck, 1972; Forstner and Wittman, 1979).

Plants can be adversely affected by all trace elements if the availability of those elements exceeds certain thresholds, which will differ with plant species, soil, and weather conditions. Normal crop yields remove only a small portion (less than 1%) of the micronutrients present. The

availability of trace elements is a function of their partitioning among different forms, which in turn is a function of solubility. This solubility is influenced by many factors. The total amount of trace element is one factor, but it is modified by pH, redox potential, texture, organic matter, clay minerals, moisture, and interrelations of trace elements (Hodgson, 1963, Sillanpaa, 1972).

Soil pH affects solubility of trace elements and therefore availability which in turn influences plant uptake. An increase in pH reduces the solubility and uptake of Al, B, Co, Cu, Fe, Ni, Sn, Zn, and especially Mn and increases that of Mo and S (Sillanpaa, 1972). The extent of the effect varies with the trace element. The change in pH may alter the adsorption or precipitation of micronutrients, and also changes plant uptake through alterations in microbial activity, change in root ion absorption or transport capability, or variations in the stability of organic matter complexes, change in solubility of antagonistic ions, or alteration of rhizosphere effects (Hodgson, 1963).

Another factor affecting trace element availability is organic matter content. The trace element level often increases with increasing organic matter with the maximum found in soils that contain 5 to 15% organic matter. With further increases in organic matter, the trace element content decreases to a deficiency level in pure peat. This is the result of plant growth and decay on a mineral soil adding subsoil trace elements brought up by roots to the

surface, so that trace element content increases proportionally with organic matter increase. With additional increases in organic matter, past 15% organic matter content, the proportion of trace elements decreases with the simultaneous decrease in bulk density (Sillanpaa, 1972).

Trace element availability is also altered by microbiological activity by a number of mechanisms:

1) decomposition of organic matter and release of inorganic ions
2) immobilization of ions by incorporation into microbial tissue
3) oxidation to a less available form
4) reduction of an element
5) indirect transformations: change in pH or Eh.

(Hodgson, 1963)

A further factor is oxidation or reduction of trace elements. The availability of Mn and Fe is more influenced by redox changes than the other trace elements (Sillanpaa, 1972). Reducing conditions are often created under conditions of high moisture (i.e. flooding) and results in increased availability of S, Cu, Mo, Ni, Zn, Pb, V, and Co. elements Mn, Fe, Mo, and S may increase in availability to toxic levels (Hodgson, 1963; Sillanpaa, 1972). The lower solubility of the trivalent forms of Mn and Fe under oxidized conditions as compared with the reduced divalent forms has been suggested as a cause of the reduced availability (Sillanpaa; 1972).

Seasonal variations also cause changes in the availability of trace elements. These changes involve many factors simultaneously. High soil temperature has been associated with high uptake of trace elements while dry soil conditions are linked to low availability. Temperature and moisture conditions control microbial activity with consequent influence on trace element availability. The availability of Cu and Zn is reduced by high P fertilization possibly because of immobilization of Cu and Zn by P, precipitation by P in plant tissue, or P-Zn antagonisms in the root, or reactions outside the root. Phosphorus fertilization has been found to increase Mn availability and have variable effects on B and Mo.

Some elements, including Pb, Hg, Cd, and Cr are hazardous to health of animals and humans even at very low concentrations. As long as these elements are bound to soil constituents in such a way that they are unavailable, there is little impact on the environment. When conditions are changed to allow increased availability, a direct environmental hazard is created. The problem of assessment of soil contamination by trace elements is complicated by lack of a simple correlation between soil trace element content and adverse effects. The environmental effects are governed by trace element mobility in the soil so that as solubility relationships of elements determine mobility they thereby determine the extent of environmental impact.

An understanding of the mechanisms of solubility and mobility of trace elements in the soil is necessary in order to efficiently use fertilizer and manure to improve quality and yield of crops without polluting the soil and groundwater. The presence of high levels of available trace elements in soil does not necessarily indicate that plant toxicities are inevitable. The amount of any trace element taken up by a plant depends not only on availability in the soil but on the species of plant and the soil and weather conditions. Many plants exclude Ti, V, Sb, Cr, and As preferentially by adsorbing only minimal amounts of these elements during nutrient uptake. (Lisk, 1972).

Aluminum

The metal aluminum is the third most abundant element (after O and Si) in the earth's crust. In soil, values range from 10.4% to 28.97% (Wolfenden, 1965).

Soils contain so much Al that soil-grown plants always take up Al from the Al-Si minerals in the soil. There is little evidence to support essentiality, but if essential, the high soil levels will make deficiencies unlikely.

As pH decreases below 7, the solubility and therefore availability of Al is very low. Below pH 5, solubility increases very rapidly with increased acidity. At pH < 5-5.5, toxic levels of Al are very probable. Soluble Al of 10 - 20 ug/g may be toxic to plants (Sauchelli, 1969). Toxicities can be prevented by liming the soil to reach a pH greater than 5.5.

Antimony

The crustal abundance of antimony is 0.2%. An equal amount is present in granite. Shale contains 1 ug/g. Soil averages 5 ug/g Sb (Levinson, 1974).

Arsenic

In the earth's crust the average value of As is 1.8 ug/g. Arsenic is more concentrated in shale, at 15 ug/g. Limestone contains 2.5 ug/g, while soil averages 1.5 ug/g (Levinson, 1974). Mattigod and Page (1983) list a wider range of As values for limestone (trace - 20 ug/g) and soils (0.1 - 40 ug/g). Dudas and Pawluk (1980) quote values for shale of 6.6 ug/g, limestone of 2.5 ug/g, and the earth's crust at 1.8 ug/g As. Yet another source lists limestone as containing 0.1 - 8.1 ug/g As, and sandstone as 0.6 - 9.7 ug/g As (Cannon et al, 1978).

Barium

Barium in the earth's crust averages 425 ug/g. The level in shale is 700 ug/g, in limestone 100 ug/g, and the range in soil is 100-3000 ug/g (Levinson, 1974). Of the alkaline earth elements, Ba is the most difficult of the ions to exchange. In increasing ease of replacement, the order is Ba> Se> Ca> Mg (Plant and Raiswell, 1983).

Barium is not known as an essential element. It is toxic to most plants, although some plants are Ba accumulators. Brazil nuts, for example, contain 3000 - 4000 ug/g Ba (Crounse et al, 1983).

Boron

Boron is in Group III of the periodic table with Al, Ga, In, and Ti. It is the only non metal among the micronutrients but is sometimes referred to as a "semimetal" (Sauchelli, 1969). It always occurs in combination with oxygen, usually in 3-fold coordination but can be found as 4-fold in a few minerals (Krauskopf, 1972). Its chemistry is influenced by its very small ionic radius. Boron has a valence of 3+.

It is agreed that B is an essential micronutrient but its biochemical role is still being investigated. Boron is thought to be involved in sugar transport through membranes, auxin metabolism, meristematic activity, water relations, phenolase inhibition, nucleic acid synthesis, meristematic activity, and protein and pectin metabolism. The roles of B in these functions are not conclusively proven (Sillanpaa, 1972; Price et al, 1972).

Estimates of the total B concentration of the earth's crust range from 10 to 50 mg/kg (Barber, 1984; Sillanpaa, 1972). In mineral form, B is present as an impurity in many rocks and minerals, although most B exists as tourmaline, a highly insoluble complex borosilicate containing approximately 3% B (Sillanpaa, 1984). Soils having less weathering generally have higher B levels than those that are highly weathered. The 4.6 mg/L of boron contained in seawater suggests that soluble B has been removed from the land masses by weathering and washed into oceans (Barber, 1984).

Boron in soil solution usually occurs as the undissociated acid, H_3BO_3. It is assumed to be in equilibrium with adsorbed B and mineral B (Barber, 1984). Available (soluble) B in soils has been estimated at 0.4 - 64.8 ug/g, averaging 17 ug/g (Sauchelli, 1969).

Availability depends on solubility and is affected by chemical, physical, climatic and biological factors (Sauchelli, 1969). Boron deficiencies have been reported in many areas of Canada (Gupta et al, 1985). Response to available B is affected by pH, moisture supply, lime content, crop, B concentration, organic matter levels, amount of leaching, and purity of applied B fertilizers. There are interactions between B and Ca, K, and P which may aggravate B deficiencies.

Adsorption of B occurs on clays and Fe and Al oxides. The oxide coatings of clay are more significant than the type of clay in influencing the amount of adsorption (Barber, 1984). Boron adsorption and fixation increases with rising pH and increasing clay content. Although B is, in general, more mobile than most other trace elements, conditions of high pH and high clay content significantly reduces movement of B through soil profiles (Sillanpaa, 1972).

Soil organic matter also fixes a proportion of the B content. Soil microorganisms compete with plants in using available B, which is transformed into various organic compounds. On the death of the microbe B is released and oxidized to inorganic forms. During drought, microbial

activity is low, there is less organic matter breakdown and more B deficiencies are noted (Sillanpaa, 1972). In addition, drought decreases water flow, and consequently reduces mass flow supply of B to roots. There is also a decreased rate of B diffusion to the root (Barber, 1984). As a result, irrigation increases the availability of B (Sillanpaa, 1972; Sauchelli, 1969). Increased pH permits increased adsorption of B. Losses of available B are mainly the result of leaching, crop removal, or transformation to unavailable inorganic compounds.

Bromine and Iodine

The two halogens, bromine and iodine, are present in very low amounts in soil and follow similar distribution patterns due to similar geochemistry (Plant and Raiswell, 1983). Bromine has not been shown to be an essential element for plants, animals, or man. Iodine is essential to animals but not plants. The halogens as a group are electronegative and tend to form negative halide ions in ionic salts. Iodine is found in seawater and salt wells as I^-, and also as sodium iodate ($NaIO_3$) (Sauchelli, 1969). Sandy soils from sedimentary rocks contain less iodine than clays and loams derived from igneous rocks (Sauchelli, 1969).

The amount of I absorbed by plants varies with species. Although most commonly ranging from 0.2 to 0.5 ug/g, plants may absorb up to 5 ug/g I. The content of I in the soil is more important in determining plant I content than is species variation.

Chlorine

Chlorine is an essential element for both plants and animals. It took nearly one hundred years to establish its essentiality because of very low requirement and difficulties in obtaining totally Cl^- free experimental conditions (Sillanpaa, 1972). Although Cl has now been established as a micronutrient the quantity required in still unknown and its biochemical role in plant metabolism is still under investigation. Potassium chloride has been reported to give better yields than potassium sulfate because the leaves of chloride fertilized plants maintain a higher moisture content and seem to have better drought resistance (Sillanpaa, 1972).

Chlorine deficiency symptoms have been reported mostly on pot experiments. Deficiency of chlorine under field conditions is rare because of its prevalence in soil and many sources of supply (Sauchelli, 1969). If Cl is present plants tend to absorb it. The amount absorbed varies from trace amounts up to several percent (Sillanpaa, 1972). Stems have higher content of Cl than leaves or heads (Sauchelli, 1969).

Chlorine is the most abundant halogen in soil, occurring most frequently as salts of Na, K, Ca or Mg. The most common valence state is -1 (as Cl^-) although the +1, +5, and +7 states are also important, and +2, +3, and +6 are also found. Chlorine compounds are highly soluble. The Cl^- ion is not fixed by soil colloids, and is susceptible to loss by leaching. In plants, Cl is in the form of water soluble chlorides.

Chromium

Chromium, a heavy metal, averages 100 ug/g in the earth's crust. Sandstone may contain 35 ug/g, shale 100 ug/g, limestone 10 ug/g and soil 5 - 1000 ug/g (Levinson, 1974). Chromium has been demonstrated to be essential to animals (Underwood, 1977).

Cobalt

Cobalt is one of the members of the iron triad, along with Ni and Fe itself. It commonly exists in the oxidation states +2 (cobaltous) or +3 (cobaltic) (Sauchelli, 1969).

The cobalt content of the earth's crust was estimated at 20 ug/g (Sauchelli, 1969) to about 40 ug/g (Sillanpaa, 1972). Krauskopf (1967) made an estimate of 25 ug/g, and noted that shale (20 ug/g) contains more Co than granite (1 ug/g). Cobalt and Ni often occur together, commonly with Fe and Cu. Arsenic is frequently present, as is S (Sauchelli, 1969).

In soil, the total Co content is usually 1 - 40 ug/g although levels may reach 800 - 1000 ug/g in the presence of cobalt minerals. Differences in availability of Co in various soils do not permit a direct correlation between total soil content of Co and the Co content of plants grown on that soil, but reports of Co deficiency are frequent on soils containing less than 3 to 5 ug/g total Co (Sillanpaa, 1972; Sauchelli, 1969). Availability of Co is related to factors such as texture, pH, and moisture content of the soil. Coarse textured soils are more commonly deficient in

Co. Cobalt is poorly absorbed by plants on calcareous soils. Drainage has been reported to have variable effects on Co uptake (Sillanpaa, 1972).

Cobalt is required by Rhizobia for nitrogen fixation, and therefore is indirectly required by legumes. Responses to Co have been reported for non-legumes but its essentiality has not been proven (Sauchelli, 1969; Sillanpaa, 1972). Legumes contain Co (0.06-0.43 ug/g dry weight) while grasses contain less (0.02 - 0.24 ug/g) and wheat grain still less (0.01 ug/g) (Sauchelli, 1969).

Iron

The earth's crust contains about five percent Fe, making it the most abundant of the nutrient elements (Barber, 1984). Iron combines with other elements to form many different secondary minerals such as hematite (Fe_2O_3), magnetite (Fe_3O_4), ferrous carbonate or siderite ($FeCO_3$), ferric carbonate ($Fe_2(CO_3)_3$), and pyrite (FeS_2). Iron is present in the primary minerals hornblende, biotite, and chlorite. The most common oxidation states are Fe^{+2} (ferrous) and Fe^{+3} (ferric). Iron complexes tend to form in both of these states (Sauchelli, 1969). In temperate soils, the total Fe usually ranges from 1 to 5 percent, bound mainly in the clay and silt fractions (Sillanpaa, 1972). In soil, iron can be present as oxides, hydroxides, silicate minerals, as complexes with organic matter, as adsorbed iron, or in solution.

High iron oxide contents are often associated with high stability of soil aggregates and high soil porosity. Iron can be removed from the soil by leaching, erosion, or crop uptake but these losses are small compared to the total content of Fe in soil.

Although the soil total content of Fe is very large and the amount required by crops is comparatively very small, deficiencies can result because of low availability (Sillanpaa, 1972). Soil pH and redox potential are the two main factors affecting the quantity of plant available Fe in soils. Generally, Fe becomes less available with increasing pH and accompanying increase in oxidation potential. At low pH and under reducing conditions Fe is in ferrous (Fe^{+2}) form which is plant available. Increasing pH and oxidation potential promote the oxidation of Fe to the more insoluble ferric (Fe^{+3}) hydroxide or oxyhydroxide form and thereby decrease Fe availability (Sillanpaa, 1972). Ferric and ferrous humates, however, are soluble at nearly all pH levels and are usually available in adequate amounts for plant growth if humus is present. Reducing conditions found in lower soil horizons promote formation of the ferrous ion to the extent that in some wet, low pH horizons the availability of Fe reaches levels toxic to plant roots (Sillanpaa, 1972).

Low oxygen content accompanied by increased CO_2 levels in the soil may allow formation of bicarbonate ions in calcareous soils. Bicarbonates may also be added to the soil

in irrigation water. These ions increase the solubility of calcium phosphates, and therefore the calcium and phosphate ion concentrations which decrease Fe availability by affecting Fe solubility in the soil and by activating Fe within the plant. On calcareous soils, lime-induced Fe chlorosis is a result of reduced Fe availability caused by high pH and high concentrations of Ca and P ions. High levels of Cu, V, or Zn ions and in particular Cu and Mn ions also contribute to decreased Fe availability, as does K deficiency (Sillanpaa, 1972; Sauchelli, 1969). Iron may be associated with soil nitrogen and phosphorus utilization (Sauchelli, 1969).

Although Fe content of plants is higher than the contents of most other trace elements it is still very low compared to soil levels. Iron content may range from 25 to 800 ug/g dependent on plant part and species. Legumes contain higher levels of Fe than grasses. Iron is required for chlorophyll production, in the cytochrome system, catalase, peroxidase, and haemoglobin, and for cell division and leaf primordia production. A deficiency of Fe results in a failure to manufacture chlorophyll. There is a consequent chlorotic mottling of interveinal areas of young leaves which is the most noticeable visual symptom of Fe deficiency.

Lanthanides

The lanthanides are a group of 15 metals beginning with lanthanum (atomic number 57) and ending with lutetium

(atomic number 71). The lanthanides have a high charge density and tend to form electrostatically bonded complexes. They are consequently quite toxic. Their toxic qualities are reduced because their oxyanion salts have an extremely low solubility at physiologic pH. Lanthanum, Ce, and Nd are the lightest and most toxic of the lanthanides. Chelated forms of lanthanides (e.g. with citrate or EDTA) exhibit highest toxicity. Compared to other metals, lanthanides are only mildly toxic. In soil most pH and pe conditions severely limit lanthanide mobility, because of the low solubilities of their salts and their strong retention on soil exchange complexes (Essington and Mattigod, 1985).

Manganese

The content of Mn in the earth's crust averages 0.08 - 0.09% (800-900 ug/g). In soils, there is a wide range of values from less than 20 ug/g to greater than 6000 ug/g. Total and exchangeable Mn are not well correlated with bedrock composition because the mobility of Mn reduces the effects of the original differences between various locations (Krauskopf, 1972).

Many factors affect solubility and uptake of Mn, so that total content of Mn in soil is a very poor indicator of availability. Soil pH and redox conditions are among the most important factors because they determine the oxidation state which in turn affects plant uptake of Mn. In soil, Mn exists as Mn^{2+}, Mn^{3+}, and Mn^{4+}. Plant roots absorb primarily Mn^{4+} which is the form predominant in aerated and

alkaline soils (Barber, 1984). It is assumed that there is a dynamic equilibrium between the forms of Mn with Mn^{4+} occurring in alkaline soils, Mn^{3+} near neutrality and Mn^{2+} in acid soils. Lower pH values favor reduction while higher pH promotes oxidation (Sillanpaa, 1972).

The manganese oxides, the most common Mn minerals in soil, are considered to hold Mn in an unavailable form. Manganese can be found complexed to organic matter. The complexes may be soluble or insoluble (Barber, 1984). The content of exchangeable and reduceable Mn increases with increasing levels of organic matter. The level of total and soluble soil Mn is highest in fine-textured soils (Sillanpaa,, 1972).

The only readily available Mn is that dissolved in the soil solution. This is a very small proportion of the total soil content of Mn. As Mn is removed by crops, leaching, erosion, or precipitation reactions, it is replaced by exchangeable Mn from the soil colloid complex. Soil organisms affect oxidation of Mn, and are most effective in the range of pH 6.0-7.9.

The soil chemistry of Mn is similar to that of Fe. Their interrelations are important to plant nutrition. These reactions are greatly affected by pH, redox conditions, and microbial activity. For best plant growth the Fe/Mn ratio should be 1.5 to 2.5. If the value is higher, it is possible to have Fe toxicity and a Mn deficiency. A ratio value of less than 1.5 may result in Mn toxicity and Fe deficiency.

There is a wide range of Mn contents in plants, varying with species, pH, and water content. For example, alfalfa may contain 14 - 936 ug/g Mn, while oat grain may have 19.5 ug/g and wheat grain 24.9 ug/g. Oats and soybeans are very sensitive to Mn deficiency. A level of less than 14 ug/g Mn in oat grain at flowering stage often results in symptoms of grey speck, a Mn deficiency disease (Sauchelli, 1969).

Manganese deficiencies are most likely to develop on soils containing less than 25 - 50 ug/g of easily reduceable Mn. A soil containing 100 ug/g or more will supply a normal crop.

Molybdenum

Molybdenum is present in soils and in the earth's crust in very small quantities. The lithosphere averages only 2.3 ug/g. Igneous rocks contain 1 - 2 ug/g, sedimentary rocks 0.2 - 3 ug/g. Shales contain higher concentrations than sandstones or limestones (Barber, 1984; Sillanpaa 1972).

The Mo content of soils usually ranges from 0.2 to 5 ug/g, averaging 2 ug/g, but values up 200 ug/g have been report (Sillanpaa, 1972). Less weathered soils have higher contents of Mo than more highly weathered soils (Barber, 1984). Of all the required elements, Mo is the heaviest. It is a member of a metal subgroup with Cr and Ni. The chemistry of Mo involves several oxidation states (+2 to +6) and formation of complex ions, including oxyanions. The total soil Mo is distributed among mineral, organic, adsorbed, and solution fractions.

Minerals containing Mo include Fe, Pb, and Ca molybdates as well as molybdanite, MoS_2, which can be oxidized to MoO_3. The Mo^{+6} is the important oxidation state. Other oxides Mo_2O_5, and MoO_2, are not plant available but may slowly transform to MoO_3. This acidic trionide is soluble in basic solution and forms molybdates. The most common is MoO_4^{2-}. This explains why Mo, unlike most trace elements, becomes more available with increasing pH. In acid soils, Al and Fe oxides may react with Mo to form insoluble and therefore unavailable Fe and Al molybdates (Sauchelli, 1969; Sillanpaa, 1972; Barber, 1984).

Soil organic matter is enriched with Mo as compared to the mineral fraction as a result of concentration of Mo in dead plant material during decomposition by microbes (Barber, 1984). Molybdenum is also present in soil as an exchangeable ion adsorbed on the soil colloidal complex. In soil solution above pH 4.2 Mo is present as MoO_4^{2-}, the form which is available to plants (Sauchelli, 1969). A high content of Fe, Mg, Cu, Mn, Zn, and Ni may cause Mo deficiency.

Similar to the PO_4^{2-} ion, Mo is quite immobile. If not removed by cropping or leaching or conversion to insoluble forms, accumulation of Mo may lead to toxicities in plants or in animals feeding on plants high in Mo. The amount of Mo absorbed by plants varies considerably with plant part, species, and soil content; ranging from 0.1 to 300 ug/g (Sauchelli, 1969).

Molybdenum is essential to Rhizobia and is therefore important to legumes. It is part of the nitrate reductase enzyme which catalyzes reduction of nitrate to ammonia. Molybdenum is required for ascorbic acid synthesis, and also plays a role in making Fe available within the plant. The presence of Mo alleviates plant injury caused by Cu, B, Ni, Co, Mn, and Zn.

Nickel

Nickel is a heavy metal and is potentially more toxic than most other heavy metals (Ni> Co>> Zn> Cu> CrO_4 > Cr = Mn = Pb). Although different species of plants display different levels of sensitivity to metal toxicity, it is a general rule that Ni is highly toxic. Areas of old mining activity may have high Ni concentrations which may lead to poisoning of vegetation. The level required to produce a detrimental effect on plants is quite low. Plants may absorb up to 5 ug/g Ni depending on species, plant part, maturity and time of sampling (Sauchelli, 1969). Nickel is considered to be beneficial to plants at very low doses, but not essential.

Nickel often increases with depth from the surface (Davies, 1983). There is a suggestion that Ni tends to be in a higher quantity in clay minerals than in organic soil components (Dudas and Pawluk, 1977).

Selenium

Selenium in the earth's crust averages about 0.1 ug/g. Rock profiles tend to show wide variation with depth. Soils

generally contain higher amounts: 0.1 - 2 ug/g Se. Very high contents of Se, up to 10 ug/g, can be found in some soils derived from Cretaceous shales and other sedimentary rocks (Sillanpaa, 1972). High rainfall or irrigation tends to leach soluble Se. In the U.S.A. and Canada, soils containing up to 6 ug/g Se in the top 20 cm are considered toxic. Phosphate fertilizers may contain up to 4 ug/g Se (Swaine, 1962). The tolerance level for feed consumed by sheep and cattle is 4 ug/g. Some plants can store 1000 to 15000 ug/g Se (Sauchelli, 1969). Soluble selenates and selenites, as well as organic Se compounds, are all plant available. Plant uptake is dependent on both availability and plant species. Selenium is a metal which reacts chemically in a manner similar to S. Selenium reacts with metals to form selenides.

Strontium

Strontium in the earth's crust has been reported at levels of 375 ug/g (Levinson, 1974). The same author lists Sr content of granite as 285 ug/g, sandstone 20 ug/g, shale 300 ug/g, limestone 500 ug/g, and soil 50 - 1000 ug/g Sr. Many radioactive elements are released by nuclear testing but most have short half-lives so that their concentrations in soil are negligible after only a few years (Reitmeier et al, 1967). Strontium-90, with a half-life of 28 years is the second most abundant radioactive element deposited on soil as fallout. There is concern about these deposits as Sr is similar in chemistry to Ca. The Sr is brought into the food

chain with Ca and is deposited along with Ca in the bones and teeth of animals and man, where it can reside for a period of many years.

Strontium, radioactive and stable, can be adsorbed onto clay minerals as exchangeable cations. The radiostrontium in this form is similar in mobility to stable Sr and Ca. In grass covered soil, downward movement is slow; in cultivated soils, however, Sr tends to be distributed through the profile, or collect mainly at the bottom of the soil profile it can move further downward. Salts, fertilizer and soil amendments accelerate downward movement.

Both soluble and exchangeable Sr are plant available. Some Sr can become fixed and therefore unavailable but it is a relatively small quantity. Roots have a larger Sr:Ca ratio than leaves, which in turn are higher than fruits and grains. Generally, plants discriminate little between Ca and Sr in uptake. The quantity of Sr taken up will vary with species and yield of crop, soil type, fertilizer and amendment applications, and cultivation (as it affects Sr distribution) (Reitmeier et al, 1967).

Titanium

The crustal abundance of Ti is 35700 ug/g. Granite contains 2300 ug/g, sandstone 1500 ug/g, shale 4600 ug/g, limestone 400 ug/g, and soil 5000 ug/g (Levinson, 1974). In herbage, Ti content is usually less than 10 ug/g. Titanium, like Fe and Al remains at or near the site of weathering and is thereby enriched in soil.

Uranium

According to Levinson (1974), Uranium occurs in crustal rock at an average level of 2.7 ug/g. A value of 2.5 ug/g is quoted by Bowie and Plant (1983). An average of 4.8 ug/g for granite and 0.45 ug/g for sandstone, 4 ug/g for shale, 2 for limestone, and 1 for soil has been reported (Levinson, 1974).

Uranium has two primary isotopes, ^{238}U which occurs in the proportion of 99.3%:0.7% ^{235}U. Nuclear energy production uses ^{235}U but has small environmental significance. Isotope ^{238}U is more important environmentally because its specific activity is greater. It has a greater number of decay products and is more radiotoxic (Bowie and Plant, 1983).

Uranium is found as a constituent of over 100 minerals, two examples being uranite, UO_2, and coffinite $U(SiO_4)_{1-x}(OH)_{4x}$. Uranium has four oxidation states, of which U^{4+} and U^{6+} are most important. Hexavalent U is extrememly mobile under oxidizing conditions, especially in acidic or carbonate-containing waters. Uranium existing as organic complexes or colloidal particles is also very mobile. It can be very strongly sorbed, however, by organic compounds and Fe sulphides under reducing conditions.

Vanadium

Vanadium, a heavy metal, is found in the earth's crust at an average of 135 ug/g. Granite and sandstone average 20 ug/g, shale 130 ug/g, limestone 15 ug/g and soil 20 - 500 ug/g (Levinson, 1974).

Vanadium has not been proven to be necessary to plants, but its essentiality to animals has been proven experimentally (Kubota, 1983). Like F, Ni, Si, and Sn, all listed as essential for animals, V is present in plants well above deficiency levels so that deficiencies are not likely to occur in grazing livestock.

Zinc

Zinc is a metal found in the same subgroup as Ca and Hg. In the earth's crust, the zinc concentration averages 80 ug/g (Krauskopf, 1972). In soils, the total content ranges from 10 - 300 ug/g (Lindsay, 1979). Total and available Zn is a reflection of the parent rock material. Limestone soils contain more zinc than soils of gneiss or quartzite parent material (Sauchelli, 1969). As with other trace elements, the total element content of the soil is not indicative of availability. Several other factors affect plant availability. Deficiencies of Zn are most common in sandy soils because most Zn-containing minerals are easily weathered to form fine-textured soils (Sillanpaa, 1972).

More than 90% of the zinc in soil is in relatively insoluble mineral forms (Barber, 1984). Sphalerite (ZnS) and smithsonite ($ZnCO_3$) are examples of Zn minerals. In montmorillonite-type clay minerals, Zn may substitute for Mg (Krauskopf, 1972). The divalent form of Zn is the most common oxidation state (Barber, 1984).

Zinc and organic matter form coordination complexes which exist in the soil organic matter fraction and as

solubl organic complexes in soil solution (Barber, 1984). Zinc has a strong tendency to form stable complex ions. The Zn^{2+} ion is the plant available form. This ion can occur in the soil solution. Zinc is also located as exchangeable ions on cation-exchange sites, as organically complexed Zn in solution, and as organically complexed Zn in the soil solid phase (Barber, 1984).

Zinc is more available under acidic conditions and tends to be less available on calcareous soils (Sauchelli, 1969). Plant residues add zinc to the soil surface. Since it is not labile, Zn remains in the top layer unless erosion occurs. A high content of clay minerals, pulverized limestone, organic matter, and Mg ions are reported to be able to adsorb enough Zn to create Zn deficiency conditions (Sauchelli, 1969).

In plant cells, Zn catalyzes oxidation processes and helps transform carbohydrates. Zinc is involved in regulation of sugar consumption, production of chlorophyll and auxins, and promotes water absorption. The amount of Zn required is about 1/100 times the amount of P.

Estimates by Swaine (1962) show fairly high but variable levels of Zn content: 50 - 1280 ug/g in phosphate fertilizer. Farmyard manure usually contains 10 to 200 ug/g Zn in dry matter.

MATERIALS AND METHODS

Since 1911, the soil samples taken approximately every ten years have been air-dried, ground to pass a 2-mm mesh, and analyzed by scientists at the Lethbridge Research Station. The remaining sample has been stored in glass jars and held in a soil storage room.

Plot 5 was chosen as a representative site for this study. It is located in the center of the plot layout, is removed as far as possible from other plot systems, and has not been subjected to disruption (as have plots 1 and 2). Plot 5 historical samples, in most cases, had adequate soil remaining to perform the desired analyses. The only exception was the 1951 surface (0-15 cm) sample in which there was insufficient sample to complete the aggregate stability and particle size analyses.

Thirty to fifty-gram subsamples were taken from the stored samples dating from 1911 to 1981 for all available depths. In order to complete the desired analyses, methods were modified to accommodate the small amount of sample available.

Samples taken in 1984 were sufficiently large to allow replication of every analysis. These samples were used as quality control indicators for the precision of each analytical technique except neutron activation analysis. Samples for neutron activation analysis were finely ground using an agate mortar and pestle, weighed into neutron activation analysis vials, and shipped to Nuclear Activation

Services, McMaster University, Ontario for analysis. In addition to the historical soil samples, samples of the triple superphosphate (0-43-0) used until 1938, and ammonium phosphate (11-48-0) in use at present, were included in the neutron activation analysis. Additional bulk samples were taken in 1985 from Plot 5 and from a site north of the plots, of the same soil series, which had never been cultivated. This new site located directly north of Rotation U approximately 200 m represented a control area. Large samples were taken from the A horizon and used for the micromorphology study, for wet sieving, dry sieving, and particle size analysis by hydrometer, as these methods could not be modified to be performed on the small historical samples.

A. Physical Properties

1. Aggregate Stability by Dispersion

Fifty ml of distilled H_2O was added to 10 g of air dry soil in a centrifuge tube. The sample was shaken for 30 minutes on an Eberbach shaker to cause partial dispersion. The entire sample was transferred to a 250 ml cylinder and the volume was made up to 200 ml with distilled H_2O. The sample was mixed thoroughly and allowed to settle. The distance of settling of a clay particle in a given time was calculated and clay-containing supernatant suspensions were pipetted off to this distance at approximately 4-hour intervals. Water was added and the sample re-mixed after each removal. The collected supernatants were dried at 30° C and weighed to allow calculation of water dispersable clay

content and give an indication of aggregate stability (McKeague, 1978).

The sample was then transferred to a beaker and treated with sonic vibration for 3 minutes to cause total dispersion (Genrich and Bremner, 1974). The sample was returned to the cylinder and clay was separated by gravity sedimentation as described above. The sum of the two clay collections is the percent clay of the particle size analysis.

Sand was sieved out of the remaining sediment, oven-dried, and weighed. The remainder of the suspension containing silt was also oven-dried and weighed (Bouyoucos, 1962).

2. Particle Size Analysis By Hydrometer:

The 2 point hydrometer method of Bouyoucos (1962) was used to determine particle size distribution on a subsample of each bulk soil sample.

3. Dry Sieving:

Dry sieving was performed on a subsample of each 1984 bulk surface sample according to the method of McKeague (1978).

4. Wet Sieving:

Wet sieving was performed on a subsample of each of the 1985 bulk samples. Another subsample was removed for moisture analysis, to be used in calculating the final result on a dry weight basis. The weighed sample was gently washed through the sequence of sieves using a minimum of water flow with very little pressure.

Fractions remaining on each sieve were washed quantatively into pre-weighed beakers and dried at 65° C. The percent sample remaining on each sieve was calculated on a dry weight basis.

5. Micromorphology:

In September 1985, 100 mm core samples were taken from Plot 5 of the Rotation U series and from a similar site of undisturbed native grass to serve as a control site. The cores were impregnated with resin and sectioned. The preparation of thin sections was performed by the University of Alberta, Soil Science Department.

B. Chemical Properties:

1. Total N and P

Samples were digested with concentrated sulfuric acid in a digestion block. The digest was analyzed for total nitrogen and phosphorus using a Technicon Autoanalyzer following Technicon Method 334-74W/B+, (released January, 1976, and revised March, 1977).

The nitrogen determination is a colorimetric method based on the formation of a green colored complex which results from the reaction of ammonia, sodium salicylate, sodium nitroprusside, and sodium hypochlorite (in solution buffered to pH 12.8-13.0). The concentration of the ammonia-salicylate complex is read at 660 nm.

The phosphorus determination is also colorimetric. A blue colored sample is formed by the reaction of ortho-

phosphate, molybdate ion, and antimony ion when followed by reduction with ascorbic acid at an acidic pH. This phosphomolybdenum complex is also read at 660 nm.

2. Total K

Total K was determined by ignition of the sample at 850 C followed by HF-HCL digestion following the method of Pawluk (1967). The K content of the dissolved samples was determined by atomic absorption spectrophotometry.

3. Total S

Total S was determined using the alkaline oxidation method of Tabatabai and Bremner (1970) followed by the sulfate analysis method of Johnson and Nishita (1952) with the colorimetric measurement of Dean (1966).

A soil sample of approximately 0.05 g was weighed into the digestion flask. Three ml of a 2M NaOH and bromine (100 ml:3 ml) mixture was added. The flask was heated to dryness and then dried for an additional 30 minutes. To the residue was added 1 ml H_2O, 1 ml formic acid, and 5 ml reducing reagent (formic acid, hydriodic acid, and hypophosphorous acid). The flask was placed on the distillation unit and the sample was distilled under nitrogen for 20 minutes. The distillate was collected in NaOH, then mixed with bismuth nitrate. The intensity of the solution color was read on a Spectronic 20 at 420 nm.

4. Soluble Salts

Soluble salts were extracted using centrifugation because the sample size was so small (5 g air-dry). The

sample was mixed with 25 ml water, shaken on a vortex mixer for approximately 30 seconds, and then centrifuged at 5000 rpm for 10 minutes. The supernatant was decanted to a 50 ml volumetric flask. A second 25 ml aliquot of distilled water was added, the pellet was re-suspended and thoroughly mixed. The mixture was centrifuged and the supernatant added to the volumetric flask. The contents were brought to volume with distilled water. The Na, K, Ca, and Mg levels were determined by atomic absorption spectrophotometry.

5. Exchangeable Cations

The water-washed soil pellet remaining after the soluble salt extraction was re-suspended in 25 ml neutral normal NH_4OAc and thoroughly mixed. The solution was centrifuged and the supernatant solution decanted into a 50 ml volumetric flask. The pellet was re-suspended in a second 25 ml aliquot of NH_4OAc, mixed, re-centrifuged, and the supernatant added to the flask. The contents were brought to volume with NH_4OAc. The Na, K, Ca, and Mg levels were analyzed using atomic absorption spectrophotometry (Alexiades and Jackson, 1965).

6. Total Cation Exchange Capacity

The pellet was re-suspended in 25 ml of $CaCl_2$, mixed, centrifuged, and the supernatant solution was discarded. The procedure was repeated with a second 25 ml volume of $CaCl_2$ and the rinse again discarded. The pellet was washed twice with 25 ml aliquots of H_2O and then twice with 25 ml aliquots of ethanol. All supernatant solutions were

discarded. The pellet was re-suspended in 1 N $MgCl_2$, using two 25 ml aliquots followed by centrifuging. The supernatant solutions were combined in a 50 ml flask and brought to volume. The Ca content of this final solution was determined by atomic absorption spectrophotometry and the total cation exchange capacity of each sample was then calculated and expressed as cmol/kg soil (Alexiades and Jackson, 1965).

7. $CaCO_3$

The $CaCO_3$ equivalent was determined using the method of Bundy and Bremner (1972).

The soil sample was placed in an Erlenmeyer flask containing a small beaker of 2 M KOH. An aliquot of 2 M HCL was injected into the flask and left to react with the soil for 16-24 hours. The CO_2 released from the soil by the acid was determined by back titration of the KOH with standard HCl.

8. Total Carbon

The total content of carbon was determined using a Leco carbon analyzer.

9. Trace Elements

The forty-two trace elements were determined by neutron activation analysis by Nuclear Activation Services Ltd. of Hamilton, Ontario.

RESULTS AND DISCUSSION

A. Physical Properties

1. Particle Size Analysis

1.1 Dispersion and gravity sedimentation

One of the most noticeable changes in the soil of the Rotation U plots after 75 years of cultivation is the increase in the clay content of the surface and subsurface soils (Figures 2 and 3). The increase in clay is most striking in the upper 15 centimetres although the 15 - 30 cm depth also shows considerable increase in clay (Figure 3). The clay content of the top 15 cm of the unfertilized half of the plot has more than doubled, from 10.8% in 1911 to 28.3% in 1984, an increase of 162% over the original values. In the 15 cm to 30 cm sample (Figure 3), the original value of 16.5% has increased to 26.1%. On the fertilized section of the plot, the 1933 values of 18.6% clay in the topsoil and 20.6% clay in the second 15 cm have increased to 26.0% and 26.7% respectively. While the percentage of clay has increased with time, both sand and silt contents have declined. The treatment of the two halves of the plot is identical, with the exception of the addition of phosphate fertilizer to the south half of the plot. Fertilizer addition is not likely to affect clay content. The difference in clay content between the fertilized half and the unfertilized half for any given year is therefore an indication of the sample variability. In some cases the difference in clay content between the fertilized and

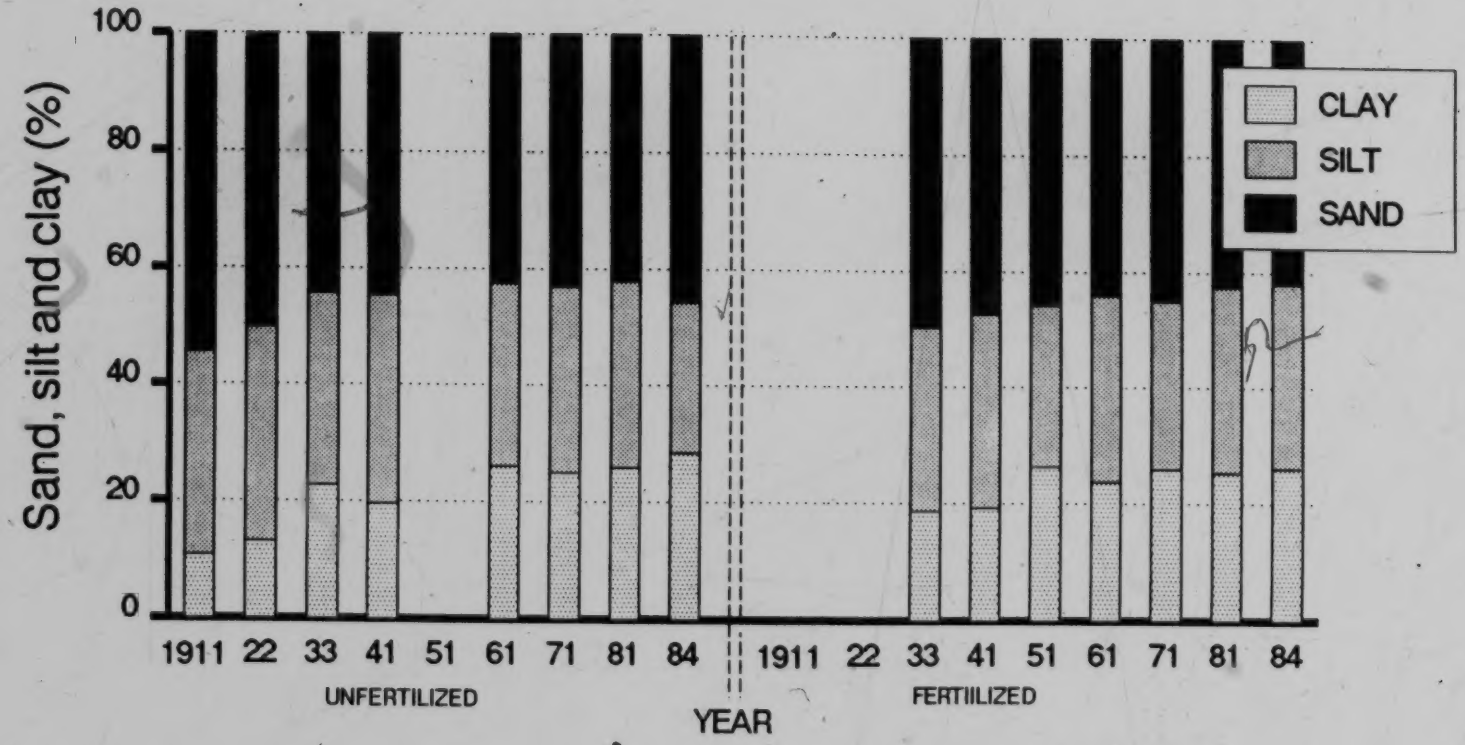

Figure 2. Content of sand, silt, and clay in 0-15 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

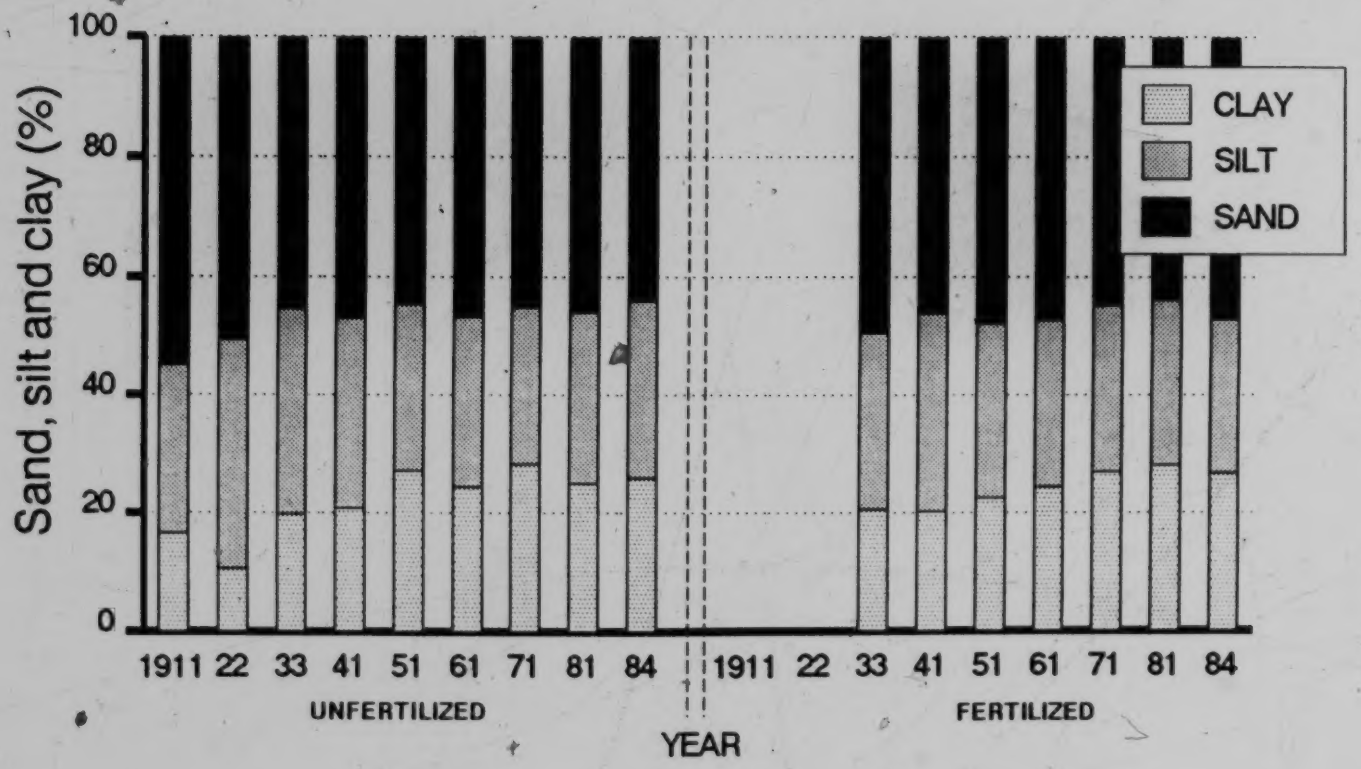

Figure 3. Content of sand, silt, and clay in 15-30 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

unfertilized sections is small, but in some instances is nearly 4%. This suggests that the plot is not uniform with respect to texture, and that conclusions based on this data must consider the amount of spatial variability.

There appears to be a trend toward increased clay content with time. The 1984 clay values are higher than those of 1911. The increase appears to have taken place in the early decades; from 1951 to 1984 very little change has occurred. Values appeared to increase but nearly the entire increase can be attributed to spatial variability in the field.

The increase in content of clay is not uniform with time; there is some fluctuation over the sampling periods. There are two possible mechanisms for the alteration in clay content. The first is the irregular effect of wind on the surface of the plots. In some years, erosion of the soil surface results in a selective removal of clay; at other times winds deposit clay particles on the plots.

Secondly, as the surface is eroded, and as bulk density increases the regular cultivations of the plot reach deeper into the subsoil. The depth of cultivation is approximately 20 cm. Clay material from the subsurface is now being incorporated into the surface soil. The clay content of the 15-30 cm depth appears to have increased with time. Incorporation of material of higher clay content from lower in the horizon is the only mechanism operating to increase clay content at this depth. While there appears to

be a trend toward higher clay content with time, some spatial variability (as evidenced by the difference in clay content between the fertilized and unfertilized halves of the plot) obscures the true extent of the increase. An increase in clay content was documented by Dalal and Mayer (1986) in Queensland, and was attributed to mixing of deeper soil with topsoil because of removal of topsoil of lower clay content by erosion. In a study by Skidmore et al (1975), mechanical analysis showed more clay in the Ap of a tilled soil than in a comparable sod area.

On Rotation U, the increase in percent clay has been levelling off in recent decades. The rate of accretion of clay appears to be only slightly higher than the rate of erosive loss of clay. Deciduous trees, planted in 1908, have functioned effectively as windbreaks on the east and west sides of the plot for many decades. Extensive building construction to the south and south-west of the plot site now protect from the prevailing west to south-west winds. Changes in soil chemistry, to be discussed later, may contribute to enhanced stability of the soil surface to erosion. Improved management techniques now in use on some farmlands west of Lethbridge also may lessen the amount of soil erosion on those areas and thereby lessening the amount of soil deposited by wind on the Rotation U plots.

1.2 Hydrometer Method:

The results of particle size analysis by the hydrometer method on the 1985 bulk samples are shown in Table 5.

The control site is considered to represent the unbroken state of natural prairie which existed in the area of the plot site in 1911. During 70 years, however, the prairie grass would have trapped and held an appreciable amount of windblown clay particles. As a result, the clay content of the control site is now 19.8%, appreciably higher than the 10.8% clay of the 1911 Plot 5 sample. Comparisons of the two values should be made very carefully, as they were achieved by two different analysis techniques and may not be not directly comparable. The clay content of the control site is lower than that of Plot 5 in 1985, indicating that the rate of accretion of clay through wind deposition and subsoil mixing of the cultivated plot has been higher than the rate of the erosion of clay. This difference in clay content between the control and the plot reflects the effect of the cultivation and cropping on net erosion by wind.

In the Rotation U soils, it is likely that most erosion took place in the first few decades after breaking. As the percentage of clay increased, with clay blown onto the plots and by incorporation from lower depths, the cohesion of clay into non erodible clods would have slowed the amount of erosion. It is seen in the data of samples from the later decades that increases in clay content have become smaller. The amount of clay accumulating through deposition and subsurface mixing must be very similar to the amount of clay being lost through wind erosion. Clay movement by eluviation to a lower horizon is considered to be an insignificant

Table 5. Content of sand, silt, and clay of Plot 5 compared to control site in 1985.

	% clay	% silt	% sand	Texture
Plot 5	28.0	22.4	49.6	Sandy clay loam
Control site	19.8	28.6	51.6	Loam

factor. Eluviation is water mediated, and the combined rain fall and irrigation water is low on the Rotation U plots.

2. Water Stable Structure

2.1 Water dispersible clay: Aggregate Stability

An aggregate separates into its component sand, silt, and clay fractions under application of sufficient disruptive force such as ultra sonic vibration. The weaker the aggregate bonding, the easier it is for the aggregate to be disrupted. Since this aggregate stability test involves only partial disruption, only the weakest aggregates will disintegrate. A higher percentage of water dispersible clay indicates the presence of more weakly bound aggregates, suggesting a lower mechanical stability of the soil structure of that sample when compared to a sample which showed a lower content of water dispersible clay and therefore a higher content of water stable aggregates.

The amount of water dispersible clay of the soil of Rotation U over 73 years is shown in Figures 4 and 5. The amount of water dispersible clay increased with time in both the fertilized and unfertilized sections of the plot until 1971. In the surface 15 cm, the unfertilized area shows a greater increase in content of weaker aggregates than the fertilized area. Root exudates and polysaccharides play a large role in binding aggregates together (Tisdall and Oades, 1982), so it is likely that the greater proportion of weak aggregates is a result of less plant growth (fewer roots and exudates) in the unfertilized section of the plot.

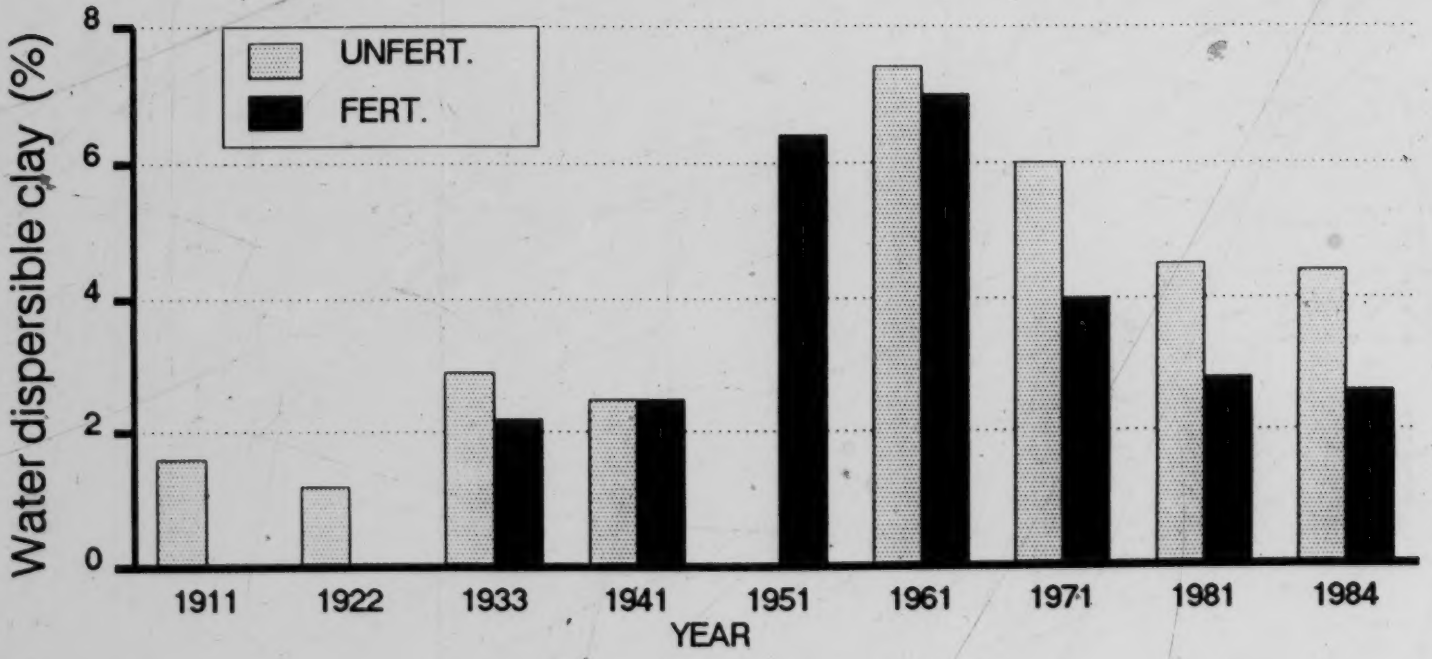

Figure 4. Content of water dispersible clay in 0-15 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

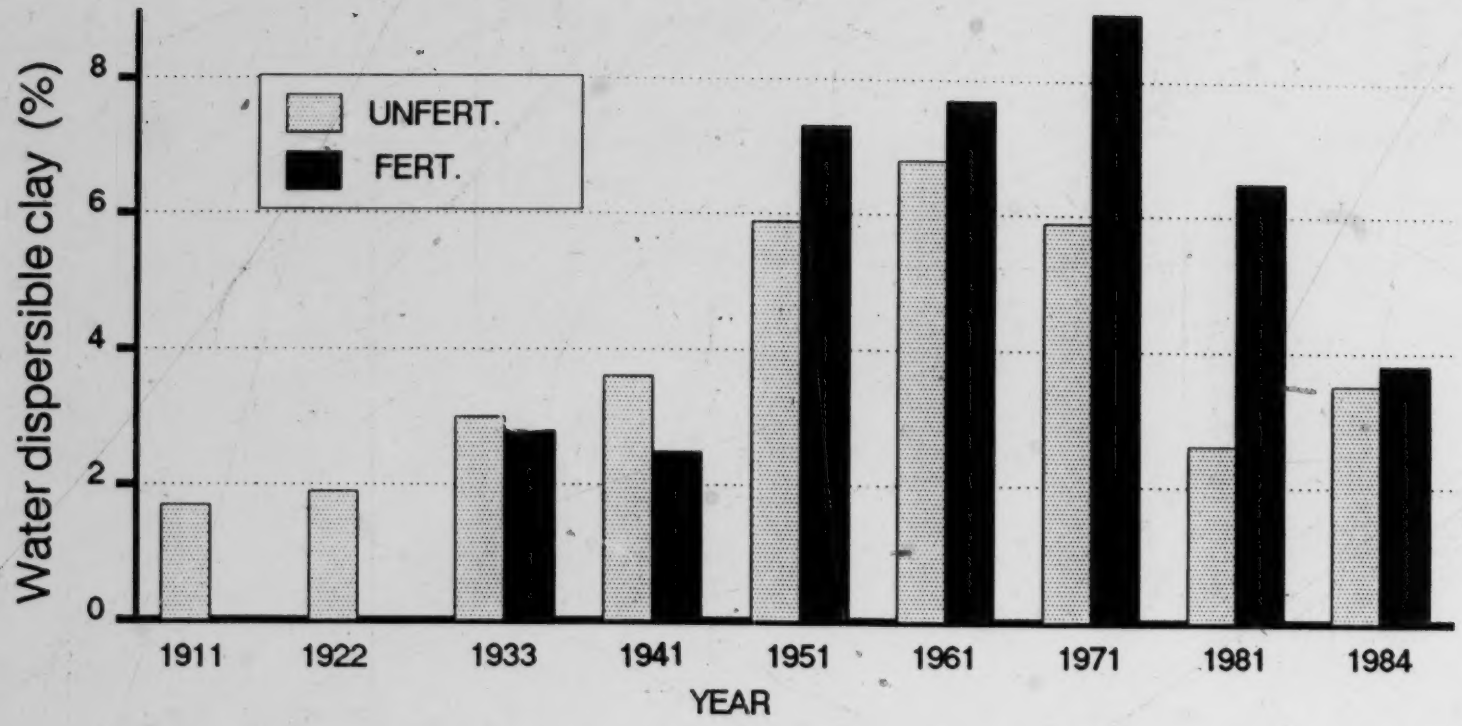

Figure 5. Content of water dispersible clay in 15-30 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

The increase with time in the content of water dispersible clay suggests a decrease in the content of water stable aggregates which in turn indicates a gradual decline in the mechanical stability of the soil under prolonged cultivation. Decreased stability under cultivation accompanied by reduced organic matter levels and increases in microaggregates was noted by Elliot, (1986).

The trend towards declining structural stability is apparent in both plot halves of Rotation U until 1961. In the following years there is a decline in the percent water dispersible clay and therefore an increase in water stable aggregates. The most recent samples in 1981 and 1984 have dispersible clay contents lower than at any time since 1951, suggesting that the plot soils are gradually becoming more resistant to breakdown by tillage, wind force, and abrasion by wind borne materials.

Water-stable primary aggregates (usually less than 1 mm diameter) are held together by water-insoluble cements and binding agents such as clay particles and various organic and inorganic colloids (Chepil and Woodruff, 1963). Secondary aggregates or clods disintegrate under the force of weather and abrasion into primary water stable aggregates. These primary aggregates accumulate in drifts as they separate easily from other soil fractions when finer particles are removed as dust and coarser materials remain behind. Drifted sand grains and water-stable aggregates are very stable mechanically and confer good tilth on soil

materials. A significant proportion of large, (greater than 1 mm) water-stable aggregates would establish wind erosion resistance in a soil. Secondary aggregates or clods are held together by water-dispersible cements which consist mainly of fine water-dispersible particles (approx. 0.02 mm in diameter). When shaken in water, these particles can be removed and the clods disintegrate to primary water stable aggregates which fail to cohere after drying. The water-dispersible fine particles are necessary to bind water-stable aggregates into clods large enough to resist wind erosion (Chepil, 1958).

The forces of cohesion between clods after soil has been wetted and dried vary greatly. Factors affecting this cohesiveness include the number and nature of wettings, pressure against soil (a function of depth), and the physical and chemical properties of the soil.

The quantities of water-dispersible silt and clay are of major importance. The greater the quantity of fine water-dispersible particles, the greater the cohesion between particles due to cementation and the greater the resistance to wind erosion after wetting and drying (Chepil, 1958).

Increased pressure also causes increased cementation. The degree of cementation and mechanical stability increases with depth until the whole soil mass may become a massive structure. Suitable tillage can break massive structure into clods and bring these clods to the surface where they contribute to increased resistance to wind erosion.

Silt, clay, organic and inorganic materials tend to cement primary and secondary aggregates together. Dispersed silt tends to act as a weak cement and resists the force of wind, although silt particles are dispersed in water far more readily than clay particles. (Chepil & Woodruff, 1963). The increased levels of Ca and organic matter in the plot soils (discussed later in the thesis) and plant exudates and polysaccharides are working together to promote and maintain aggregates. These factors may explain the decrease in water dispersible clay and increase in water stable aggregates shown in recent decades.

2.2 Wet sieving

Wet sieving simulates the forces that break down clods and aggregates in the field. Most soils contain large pores immediately following cultivation. When the soil is wet under tension, the soil slakes and slumps and the pores fill. When a soil is dry and suddenly is wetted, air trapped in aggregates causes tiny explosions which assist in breaking down aggregates. A more nearly complete breakdown of aggregates from tilled soil (compared to grassland) indicates that the formation of surface crusts is likely (Skidmore et al, 1975).

The bulk samples taken in 1985 were used to determine aggregate stability by wet sieving (Table 6). Under the disruptive effect of water, more particles from the plot soil passed a 200 mesh sieve than from the control site. The

Table 6. Results of wet and dry sieve analyses of bulk samples from plot 5 and control site in 1985.

Sieve No. Mesh	mm	Plot 5 % soil retained	Plot 5 % cumulative weight	Control site % soil retained	Control site % cumulative weight
		Wet sieving			
4	4.76	0.24	0.24	0	0
10	2.00	0.06	0.30	0.47	0.47
18	1.00	0.23	0.53	0.42	0.89
30	0.595	0.23	0.76	0.39	1.28
40	0.425	0.23	0.99	0.57	1.85
60	0.25	2.01	3.00	3.02	4.87
100	0.15	9.21	12.21	15.40	20.27
200	0.074	19.89	32.10	18.63	38.90
Passed 200		67.90		61.13	
		Dry sieving			
4	4.76	0.04	0.04	0.02	0.02
10	2.00	7.04	7.08	5.88	5.90
18	1.00	24.17	31.25	12.77	18.67
30	0.595	14.81	46.06	7.61	26.28
60	0.25	12.99	59.05	7.52	33.80
100	0.15	12.86	71.91	13.61	47.41
200	0.074	13.02	84.98	22.64	70.05
Passed 200		15.02		29.95	

control site has a higher content of water stable aggregates, and therefore greater wind erosion resistance. The difference is not very great, suggesting that structural deterioration on the plot has been minimal. Comparison with the water dispersible clay data indicates that the differences were more marked twenty years ago but the structural stability has improved over the past two decades.

2.3 Dry sieving

The dry sieving technique shows the reverse trend (Table 6). There is a higher percentage of large aggregates in the plot soil when it is dry. The dry soil has a tendency to form hard crusts creating an unfavorable environment for water penetration and plant growth. The control site remains more friable, suggesting again that it has better soil structure characteristics. The larger aggregates and surface crust of the plot site does tend to limit wind erosion.

3. Micromorphology

Microscopic examination of thin sections prepared from the soils of the plot site and the control site revealed visible differences. The control site has a more open fabric; a greater porosity and a higher proportion of large voids (Plate 1). The soil aggregates and particles are generally larger. In contrast, the soil from the plot site is much more densely packed in appearance (Plates 2 and 3). The fine soil particles are closely arranged and are interspersed with fewer, smaller pores. In a study comparing cultivated plots to grass areas, Skidmore et al (1975) noted

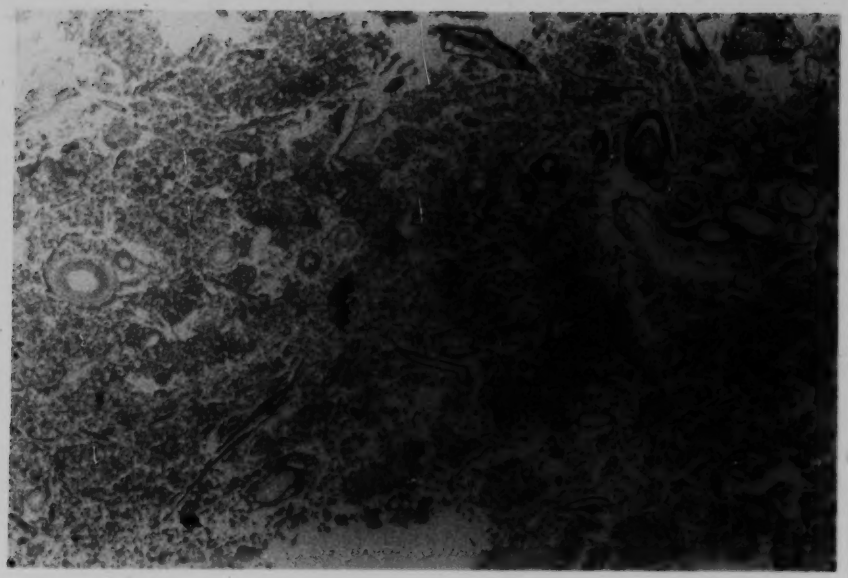

Plate 1. Micrograph of control site.
(3x magnification)

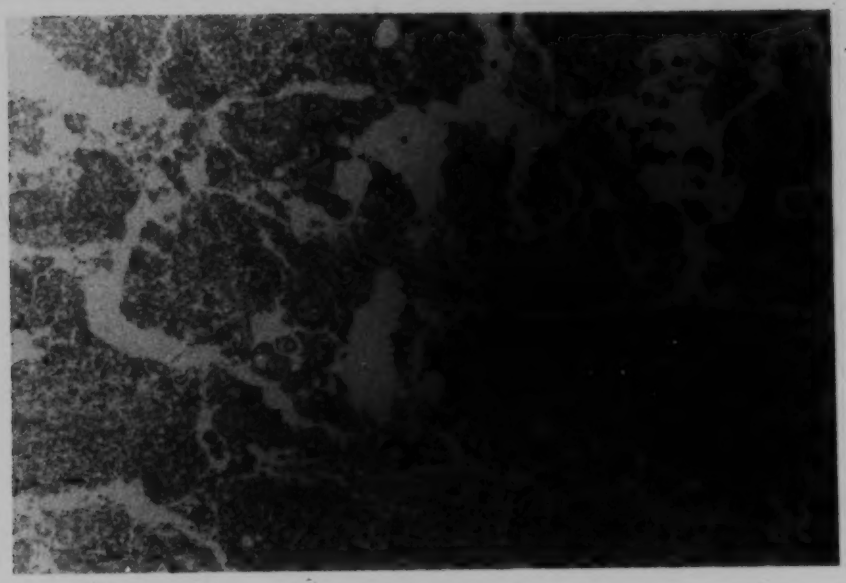

Plate 2. Micrograph of Ap horizon of plot 5 showing fragments of Bm admixed with A. (3x magnification)

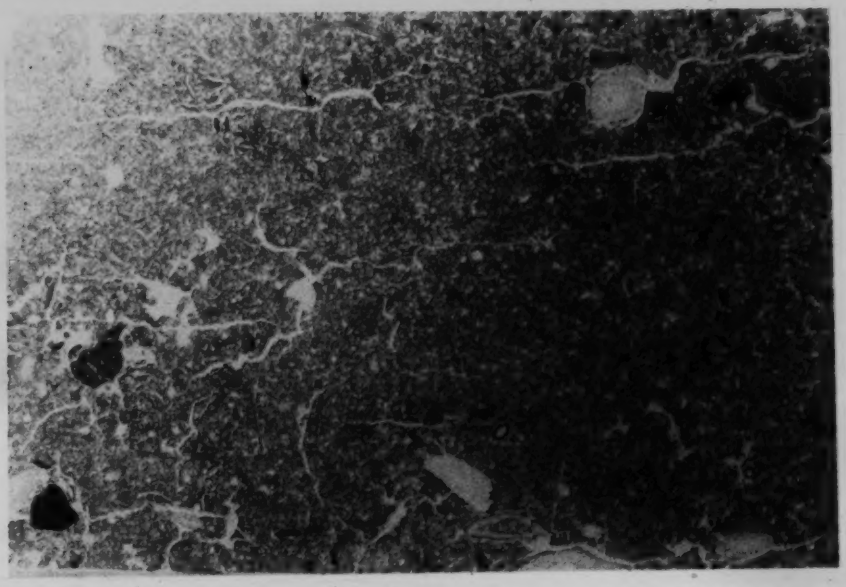

Plate 3. Micrograph of Ap horizon of plot 5 showing compacted structure. (3x magnification)

that election micrographs showed more roots and cavities in the aggregates from the sod.

The native grass cover of the control site has contributed to the development of a strongly structured open soil which provides optimum physical conditions for plant growth. The greater degree of compaction is to be expected in the soil of the plot site. The many years of tillage operations by horses and by heavy machinery, the successive cropping, and the exposure of the open soil to extremes of winter weather would work together to break down soil aggregates. Thirty-five years of cultivation of four soils of the Ottawa Experimental Farm resulted in increased bulk densities at all four sites indicating that compaction had occurred (Coote and Ramsey, 1983). The four sites included three Melanic Brunisols and one Humic Gleysol ranging from loamy sand to clay in texture. The soil structure, of these Ottawa soils however, is not massive. The soil remains an arrangement of aggregates with adequate open pores for water management, gas exchange, and root penetration. There is little evidence of erosion on these four sites. Rotation U shows similar effects.

B. Chemical Properties:

1. Total Carbon and Organic Matter

Calcium carbonate is 12% inorganic carbon. If the amount of inorganic carbon (from $CaCO_3$) is subtracted from the total carbon, the remaining amount is the organic carbon. Multiplication of the organic carbon value by a

factor of 1.7 will approximate the percent organic matter.

The total C level (Figures 6 and 7) is an indication of organic matter content. The percent inorganic carbon as determined by $CaCO_3$ analysis (Table 7) was subtracted from the total percent carbon. The remainder was multiplied by a factor of 1.7 to give an estimate of organic matter content (Table 8).

Loss of organic matter on cultivation has often been documented and the subsequent loss of nutrient supplying capacity and soil structural stability are of great concern. Loss of organic matter and deterioration of soil structure appear to be critical factors in the amount of yield loss with erosion (Dormaar et al, 1986). The total percent C of the Rotation U shows a steady increase with time. Most of this increase is accounted for by the rise in percent $CaCO_3$ which is nearly 12% inorganic carbon. When the percent total C is corrected for this contribution, and multiplied by a factor of 1.7 to create an organic matter content estimation, it can be seen that there is some variation in the organic matter content of the plots with time; the initial 1911 value of 3.3% organic matter in the surface soil has increased to 3.7% in 1984. Consideration of field variability suggests that a claim of even slight rise may be over stated. The variation in results over time may possibly be due entirely to spatial variability. There is, however, no indication at all of the major declines in organic matter content that appear in the literature. The manure amendments

Table 7. Content of inorganic carbon (%) of plot 5 soils from 1911 to 1984.

Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized									
0 - 15	0.036	0.036	0.156	0.132	0.156	0.336	0.384	0.432	0.480
15 - 30	0.192	0.024	0.672	0.228	0.648	0.576	0.576	0.588	0.672
30 - 60						2.400	2.208	2.256	
60 - 90						1.764	2.112	2.088	
Fertilized									
0 - 15			0.168	0.060	0.144	0.240	0.432	0.300	0.480
15 - 30			0.432	0.048	0.264	0.432	0.744	0.624	0.650
30 - 60						1.800	2.100	2.184	
60 - 90						1.920	2.208	1.920	

Table 8. Content of organic matter (%) of plot 5 soils from 1911 to 1984.

Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized									
0 - 15	3.3	2.4	3.4	4.3	4.0	3.6	3.7	3.3	3.7
15 - 30	2.3	1.9	3.1	3.2	3.1	3.2	2.8	2.8	3.1
30 - 60						1.4	1.5	1.5	
60 - 90						0.9	1.0	1.0	
Fertilized									
0 - 15			3.1	3.6	3.4	3.6	3.5	3.8	3.7
15 - 30			3.1	2.7	2.9	2.9	2.8	2.8	3.2
30 - 60						1.5	1.5	1.6	
60 - 90						0.9	1.0	1.2	

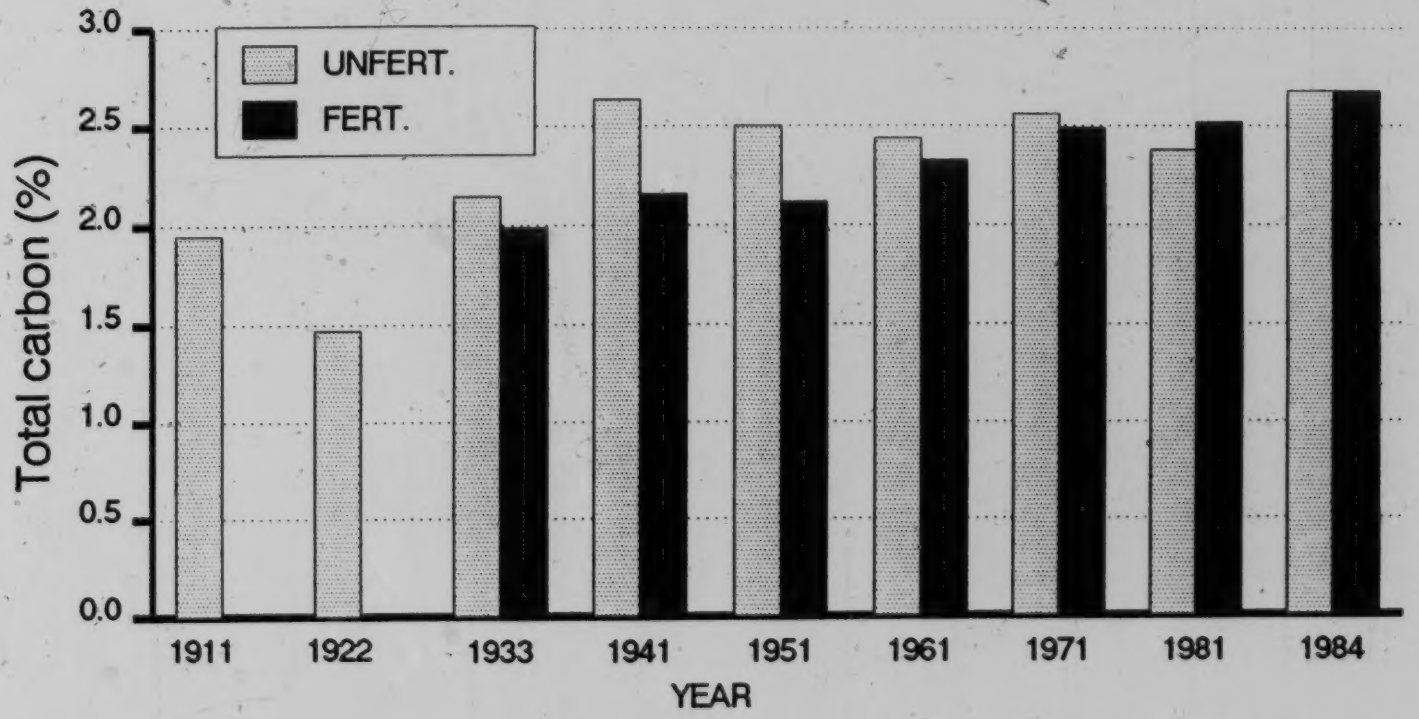

Figure 6. Content of total carbon in 0-15 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

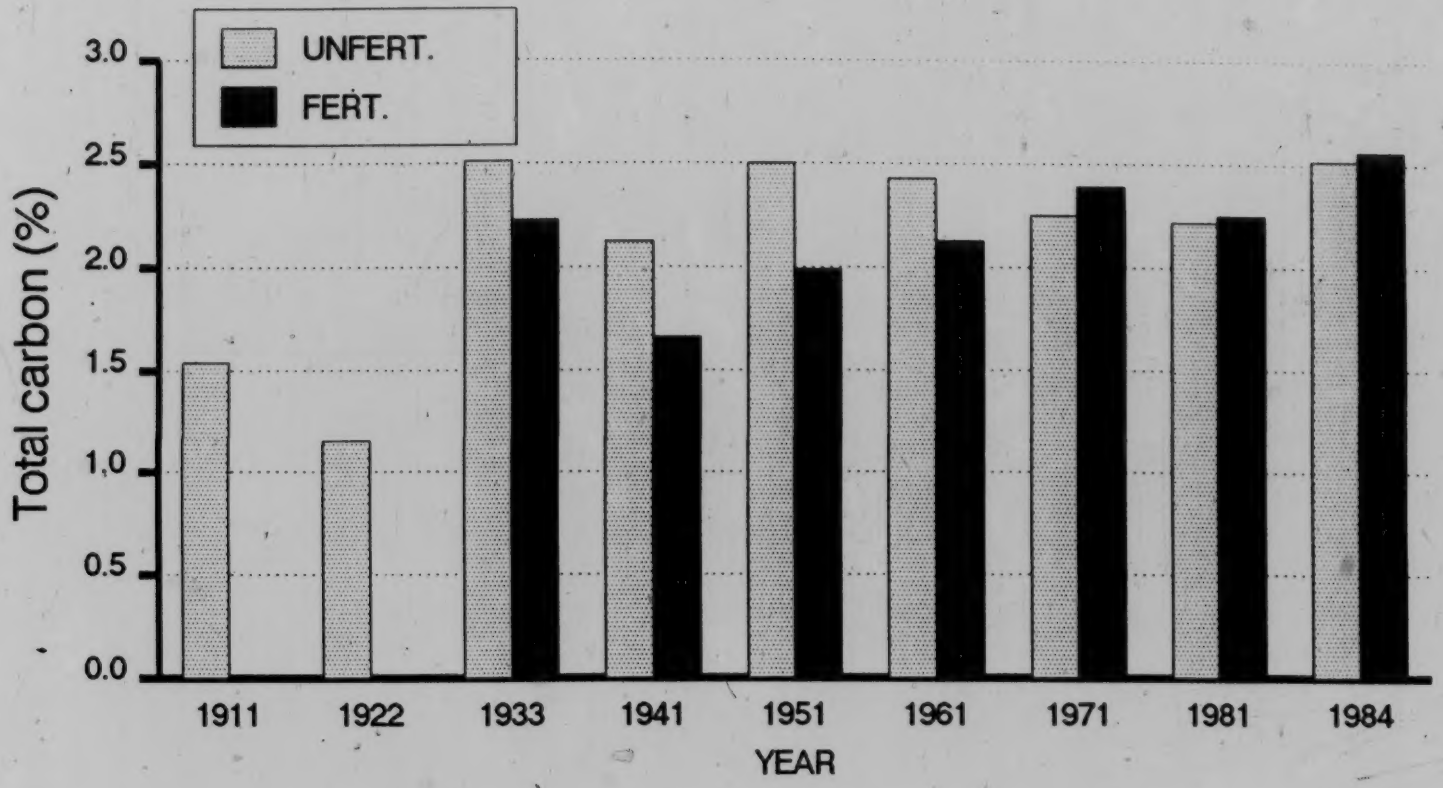

Figure 7. Content of total carbon in 15-30 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

and residue incorporation have maintained the organic C level. Manure applications have often been reported to have benefical effects. Manure reduces bulk density, reduces surface crusting, promotes soil aggregation, and builds up soil organic matter (Sommerfeldt and Chang, 1985). It is also suggested that manure improves crop yields by improving nutrient supply and by affecting humus colloids to improve the physical environment (Campbell et al, 1986).

References to deterioration of organic matter levels with cultivation are numerous (Newton, 1945; Hill, 1954; Haas, 1957, Dubetz et al., 1975; Dormaar, 1979; Tiessen et al., 1982). The inclusion of legumes in the crop rotation and addition of barnyard manure slows this decline and under proper management the trend can be reversed to cause an increase in organic matter content (Hill, 1954; Tanchandrphongs and Davidson, 1970; Pittman, 1977; Odell et al., 1984).

Although high organic matter permits good tilth and promotes soil fertility, it also enhances erodibility. Soils containing high amounts of decomposed organic matter also contain more wind-erodible fractions than soils containing less humus, and are more susceptible to wind erosion. (Chepil & Woodruff, 1963). Earlier work by Chepil (1955) indicated that under conditions of rapid decomposition of vegetative matter the content of water-stable aggregates greater than 0.84 mm in diameter increased, the content of fine water-stable particles less than 0.02 mm decreased, and

erodibility by wind decreased. The decrease in erodibility was more pronounced and longer lasting with greater vegetative matter additions. The decline in erodibility, however, can be reversed within 2 to 3 years by ceasing organic matter additions. Once the vegetative matter is completely decomposed, soils will then show a significantly lower degree of cloddiness. At that time, soils then become more erodible than before the orgnic matter additions. The effect of decomposition of vegetative material on soil aggregation and deaggregation is mainly the result of the binding action of cementing substances produced by microorganisms to form aggregates (Chepil & Woodruff, 1963). Elliott (1986) suggested that organic matter which binds microaggregates into macroaggregates (primary into secondary) is the primary source of nutrients released when organic matter is lost on cultivation. The cementing substances may consist of colloids from decomposed plant residue, microorganisms and their secretion products, and polysaccharides. The cementing effects are temporary. The eventual breakdown of cements allows disintegration of aggregates and the result is a more erodible soil condition than that of the soil before residue addition. Continual organic matter additions are required to counteract the tendency to increased erodibility caused by secondary products of organic matter decomposition. Soil stabilization and conservation, and soil fertility require a balance between vegetative cover and organic matter additions (Chepil & Woodruff, 1963). On

Rotation U, the applications of manure and incorporation of sugar beet tops, third year alfalfa crops, and grain stubble all add organic matter to the soil and its decomposition should lessen the susceptibility of the soils of the plots to wind erosion. If organic matter additions to Rotation U are stopped, increased erosion by wind can be expected.

2. $CaCO_3$

The $CaCO_3$ content has increased dramatically since 1911 in both fertilized and unfertilized sections of the plots (Figures 8 and 9). Inputs of Ca, carbonates, and bicarbonates mainly from irrigation water but also from manure, fertilizer, and vegetation residues react together and precipitate out as $CaCO_3$. There is a strong carbonate layer below the 30 cm depth. With continued erosion and cultivation, $CaCO_3$ is being brought nearer to the surface from deeper in the soil. Some $CaCO_3$ may be brought up with water-table fluctuations. Increased $CaCO_3$ content from these sources has caused a pH increase from 7.1 to 7.6 in the surface soil (Dubetz, 1983). The pH and $CaCO_3$ levels are still rising, but increases have been smaller in recent decades. Further dramatic increases in pH values are unlikely as the soil approaches the pH maintained by the reaction of $CaCO_3$.

Several researchers have noted that high lime ($CaCO_3$) content increases erodibility (Hopkins, 1935). The more $CaCO_3$ added, the greater the decrease in cloddiness and

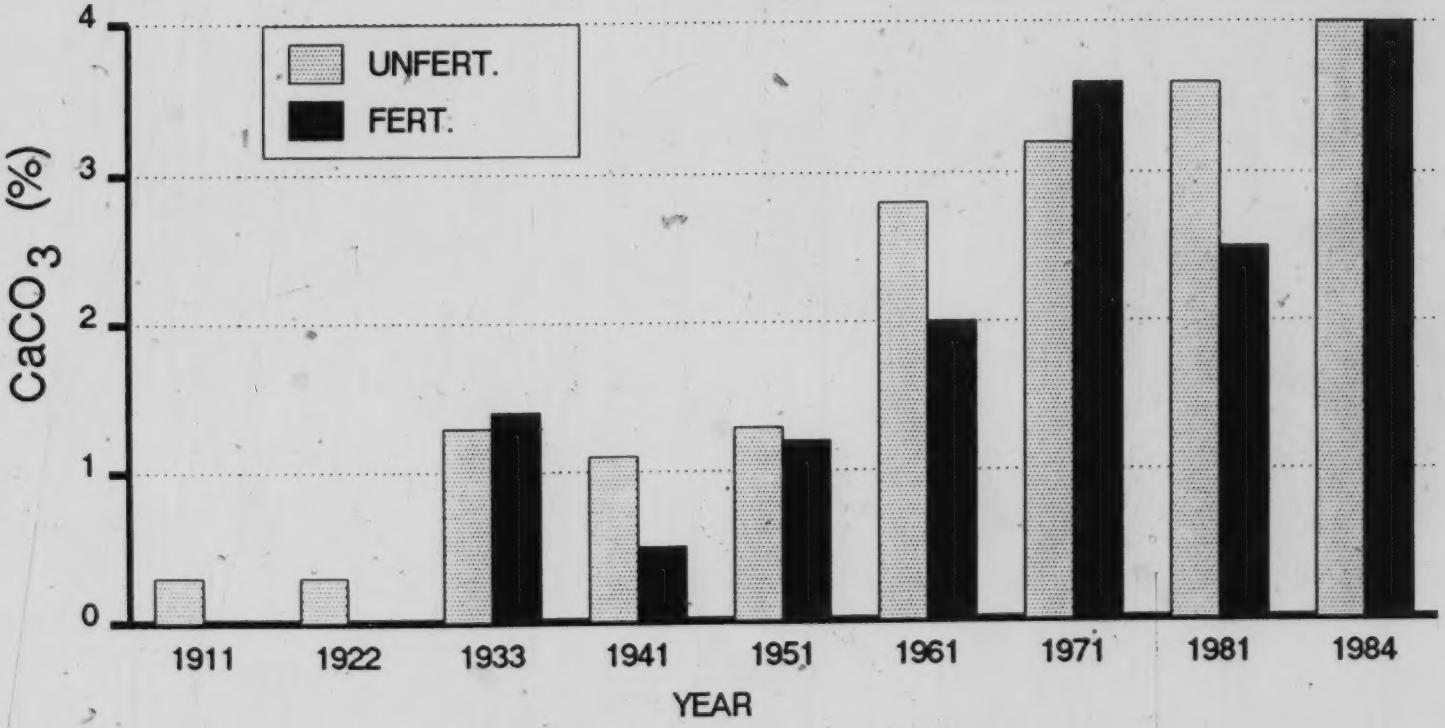

Figure 8. Content of $CaCO_3$ in 0-15 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

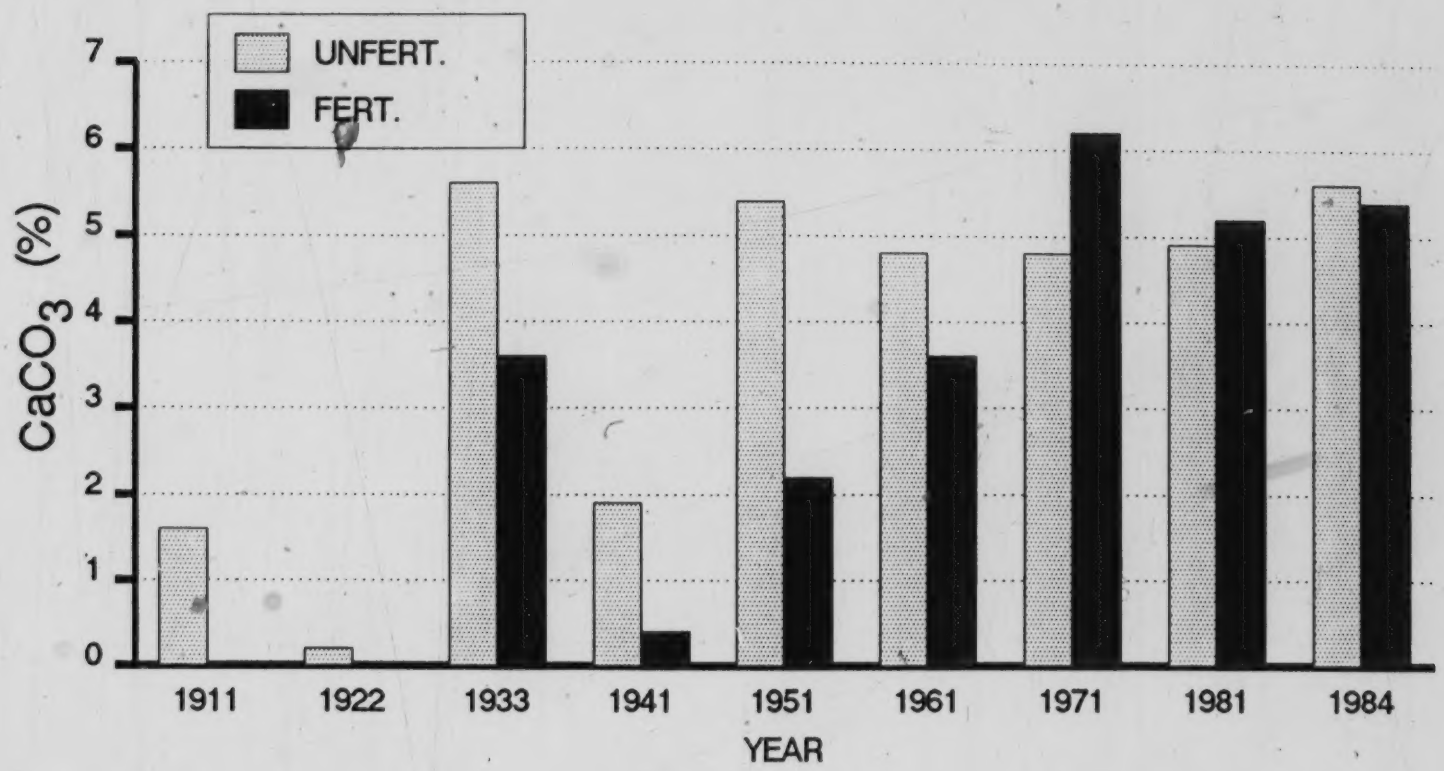

Figure 9. Content of $CaCO_3$ in 15-30 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

mechanical stability and the greater the increase in erodibility. The effect remains as long as $CaCO_3$ remains in the surface soil (Chepil & Woodruff, 1963). According to Chepil and Woodruff (1963) $CaCO_3$ seems to counteract the cementing strength of clay and allow clods to soften and granulate. If the granules are small enough they will be eroded easily by the wind (Hopkins et al, 1946). The $CaCO_3$ does not appear to affect the primary or water stable aggregates. It only weakens the bonds that hold these aggregates together in clods. Exposure of the $CaCO_3$ horizon by erosion or cultivation promotes further erosion. This happens commonly on knolls which then allow the scattering of $CaCO_3$ and promotes further spread of erosion.

Over the past 75 years, the increase in $CaCO_3$ of the soils of Rotation U have rendered the plots increasingly susceptible to erosion. Very little evidence of erosion, however, is evident on the site. The management techniques employed on Rotation U included the planting of shelter belts, maintenance of vegetative cover, provision of adequate moisture, and the continual additions of organic matter. These techniques appear to have successfully balanced the erosive tendencies which are to be expected of soils containing high levels of $CaCO_3$ in the surface horizon.

3. Total N

Contrary to many published reports (Newton et al, 1945; Hill, 1954; Haas, 1957; Martel and Paul, 1974; Dormaar, 1979; Gregorich and Anderson, 1985), cultivation for 75 years did not cause a lasting drop in the total content of nitrogen in Rotation U soils.

In the unfertilized section of the plot, the total N content of the surface soil (Figure 10) dropped in the decade immediately following the initial breaking. By 1933, the level had recovered and surpassed the original value. If the differences between the fertilized and unfertilized sections of the plot are considered to be indications of variability, then sufficient variability exists to weaken any further suggestions of a trend. Rather, the total N contents of the surface soil samples from 1933 to 1984 are so close in value as to be considered identical throughout the life of the plot. The total N content of the 15-30 cm depth (Figure 11) did not appear to be much affected by the initial breaking, but by 1933 the N content of the lower depth also increased and then remained at a fairly constant level for the remainder of the lifetime of the plot. This maintenance of total N levels over the last 50 years mirrors the lack of major increases or declines in organic matter contents.

The particle size analysis shows a reduction in clay in 1922, similar to the decline in organic matter and total N. This may have been the result of erosion in which aggregates

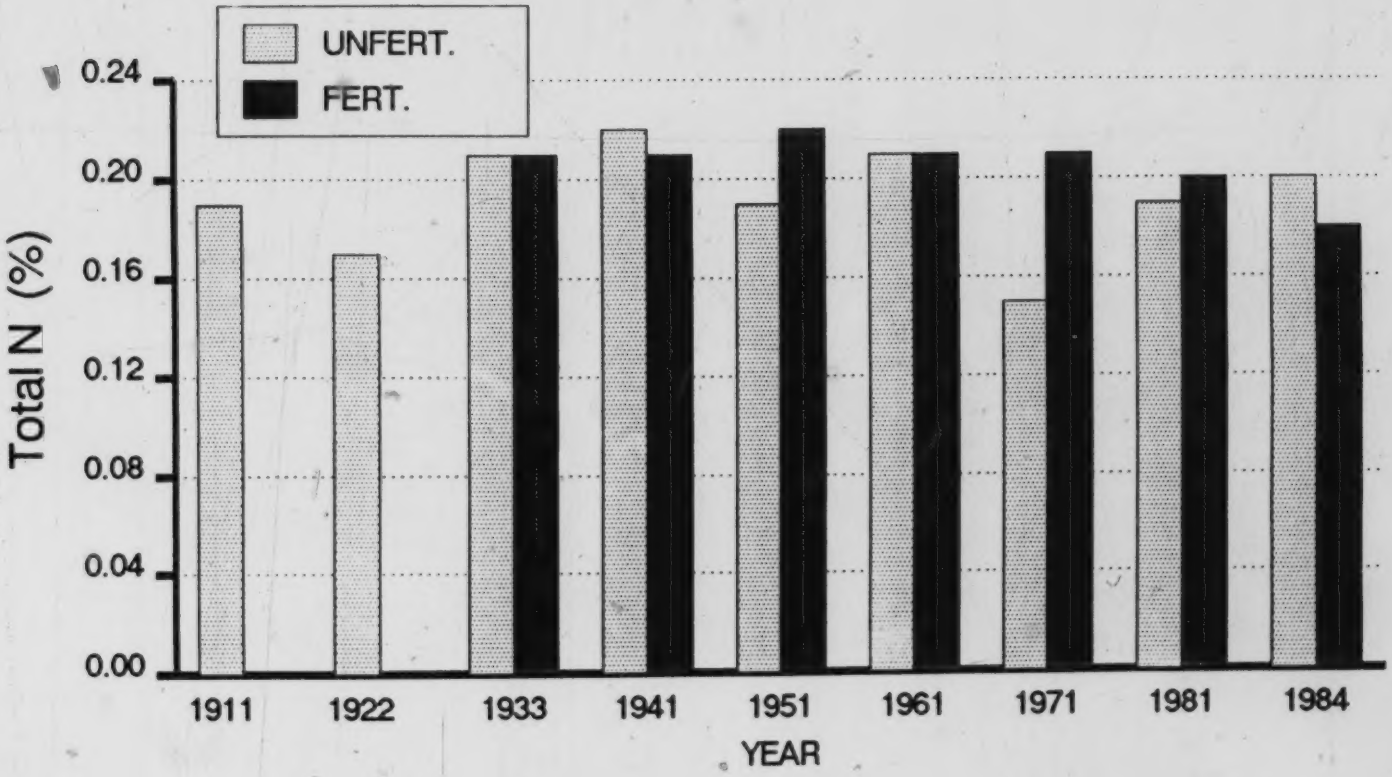

Figure 10. Content of total N in 0-15 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

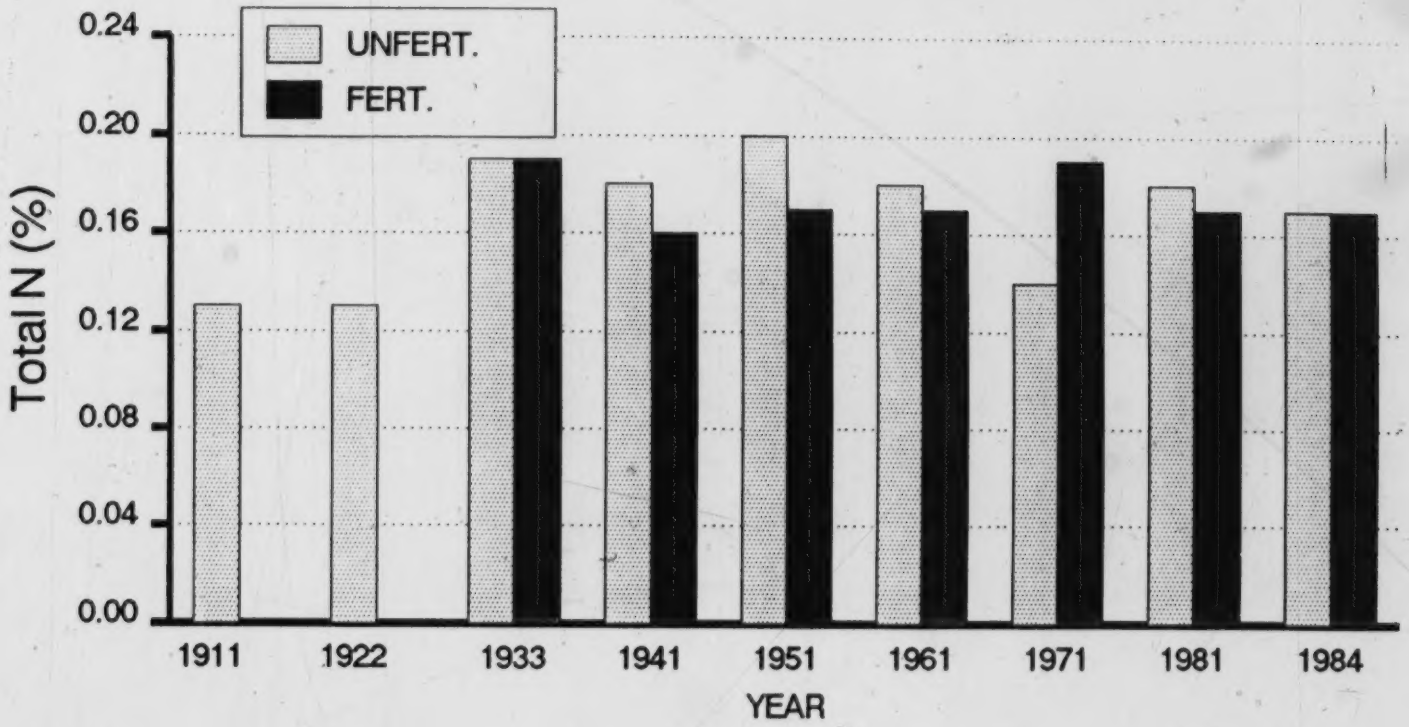

Figure 11. Content of total N in 15-30 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

containing clay, organic matter, and associated N were blown away. Much work was being done on erosion at the Lethbridge Research Station at that time, and erosion control practices were begun. By 1931, these measures were beginning to have a significant effect in conserving the soils of the Research Station. Other farming areas were not so swift to adopt conservation practices, and their soils continued to drift. With effective shelterbelts, vegetative covers and rough cultivation, the plots began to trap drifting soil. These accretions tended to increase the surface clay, maintain the organic matter levels and total N contents.

At both depths there is a sharp drop in total N in 1971 which is not reflected in the organic matter values. The irrigation system was switched from a flood to a sprinkler system in 1967 and the subsequent drop in the water table may have allowed nitrates to be washed out of the top 30 cm of the soil. The system brought itself back into a steady state condition by the 1981 sampling. The fertilizer applications maintained the N content levels in the fertilized section of the plot. The higher yields of the fertilized section might have been expected to deplete the N content, but this does not appear to have occurred here. No deficiencies are developing in either area, so the nitrogen inputs are keeping pace with plant demand and losses by leaching or denitrification. Neither is there any major accumulation of nitrogen; the inputs and removals of nitrogen appear to balance closely. Dubetz (1983) noted similar trends.

Dark Brown Chernozems placed under cultivation are often reported to have declined in nitrogen content. After 26 years, 37% of the nitrogen had been lost according to a report by Newton et al (1945). Martel and Paul (1974) showed a loss of 49% of soil N after 60 years of cultivation of a Black Chernozem. Dormaar and Pittman (1980) discovered 46% less N in a cultivated Dark Brown Chernozem than on an adjacent grassland. Each of these studies, however, involved the investigation of only one soil, or pair of soils, and therefore the data should be studied with consideration given to the sample size. The stability of the total N levels on the Rotation U plots is likely a result of the higher percentage of alfalfa crops in the rotation, the addition of manure and fertilizer, the plowing under of some residues, and the accretion of nitrogen rich topsoil. Under this system, it is not possible to separate the individual contributions of each of these sources. The beneficial effects of alfalfa in crop rotations on N levels has been substantiated in other situations (Haas et al, 1957; Tiessen et al., 1982; Odell et al., 1984), and are noticeable under both irrigated and dryland conditions. Manure applications to raise N levels have been recommended by Odell et al (1984), who cautioned that an integrated program of soil management which includes legumes in crop rotation, manure and fertilizer treatments, is necessary for maintenance of N levels.

4. Total P

The level of total P shows some variation with time and overall appears to show a slight rise (Figures 12 and 13). Spatial variability in the field again prevents a definite description of any trend. The fertilized and unfertilized sections show very close parallels. The lower crop yields of the unfertilized section have used less P than the higher yielding fertilized area so the levels in both halves of the plot are remaining remarkably similar.

Both plot sections show a drop in percentage P at the time of the 1971 sampling. The irrigation system was switched from flood irrigation to a sprinkler system in 1967. It is likely that soluble forms of P were leached downwards with the new system and that years elapsed before a new steady state condition was established.

Again, a rise in percentage P or even maintenance of P levels is not expected under cultivation. Tiessen, Stewart, and Bettany (1982) indicate that P losses under cultivation can be expected to be approximately 0.3% per year of cultivation. On Rotation U, the addition of P fertilizer and manure is maintaining soil P levels. Similar trends have been noted in a study by Dubetz, Kozub, and Dormaar (1975) in which 33.5 tonnes/ha of manure every four years increased soil P levels. Gregorich and Anderson (1985) also record evidence of long term cultivated soils maintaining P levels similar to original values through use of fertilizer.

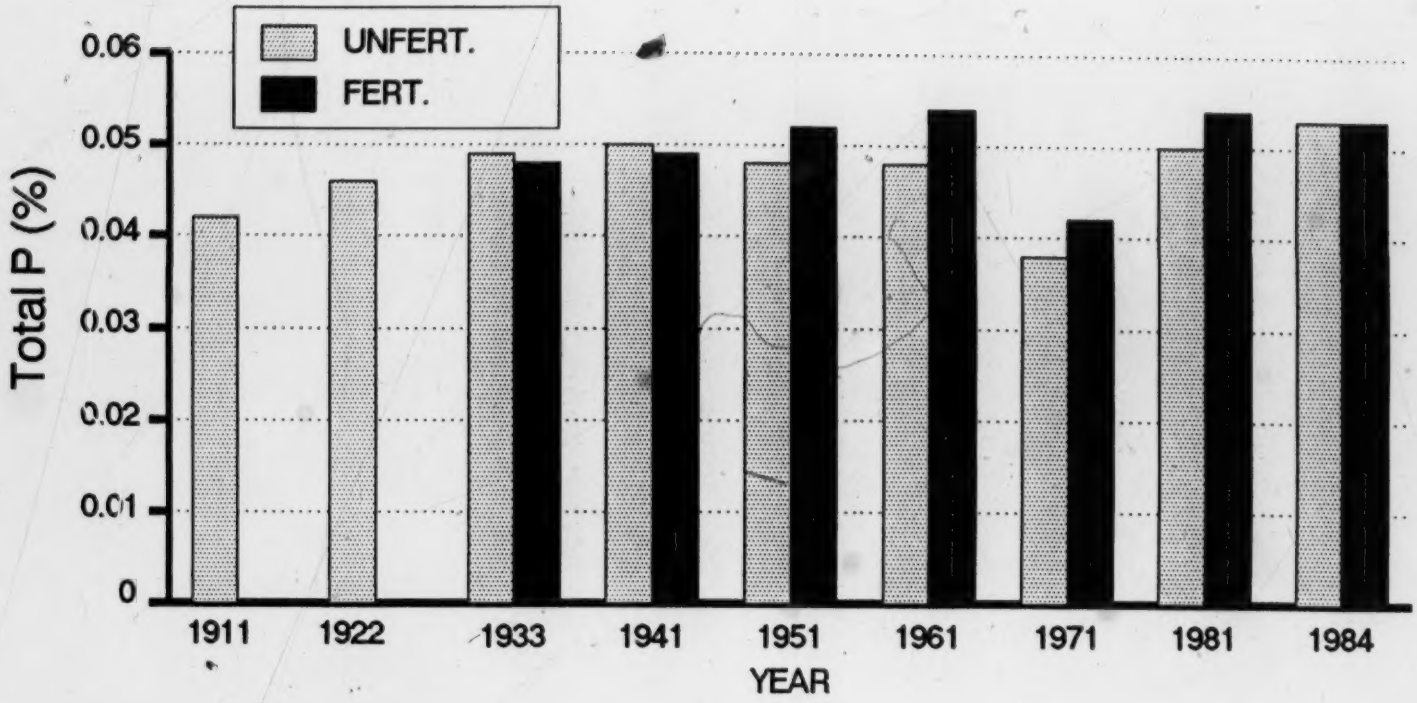

Figure 12. Content of total P in 0-15 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

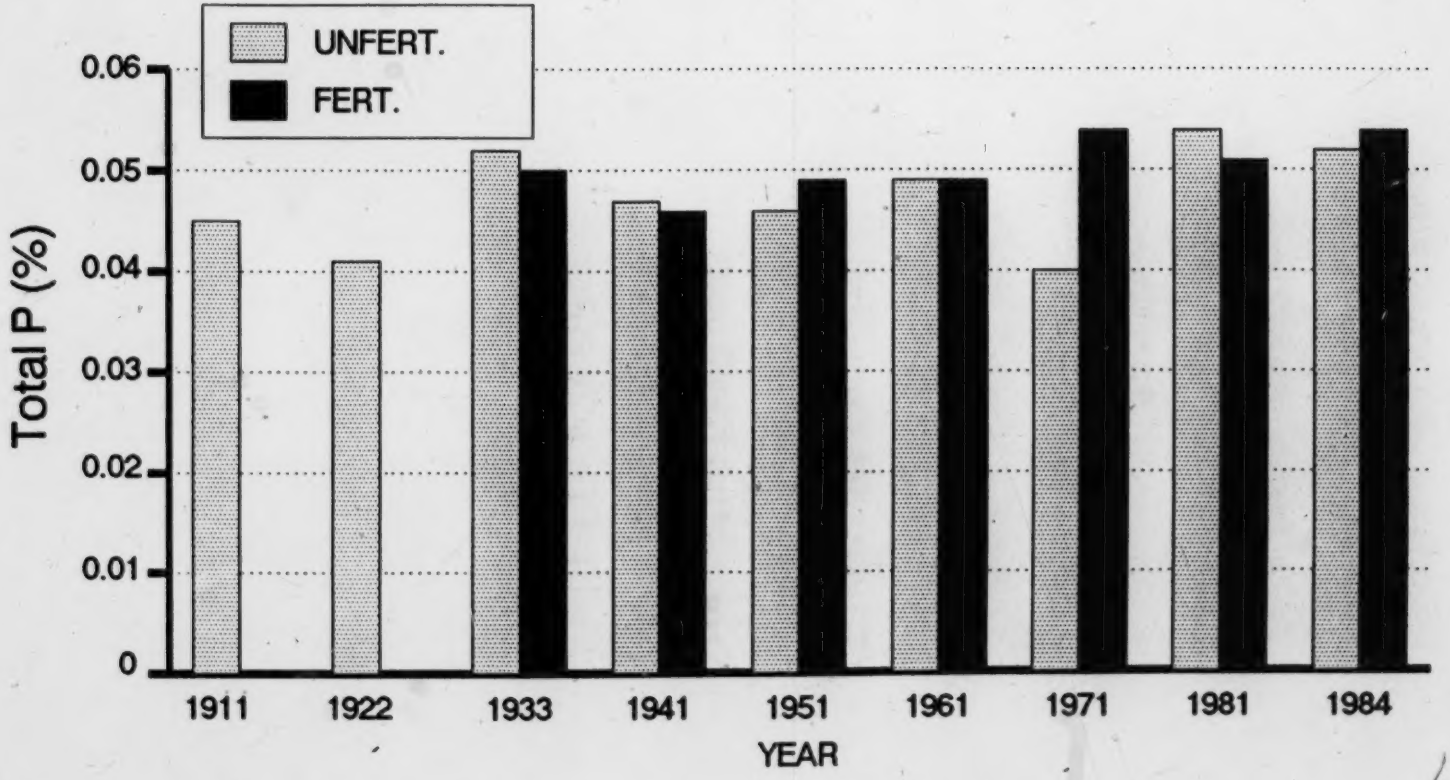

Figure 13. Content of total P in 15-30 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

5. Total K

Figure 14 shows the total K content of the soils of the surface 15 cm of Plot 5. The unfertilized section shows an initial increase in total K levels from 1911 to 1941, followed by small fluctuations from 1941 to 1971, and finally a decline in K content during the final two samplings. The fertilized half of the plot shows its highest K value at the first sampling in 1933. There is a marked decline to the total K level of 1941, followed by successive increases in 1951 and 1961. Another decline to the 1971 level is followed by two very similar total K values in 1981 and 1984.

Using the difference between the K content of the fertilized section and the unfertilized section as an indicator of sample variability, there is evidence of considerable variability in K content results. If K values of the fertilized and unfertilized sections of the plots are averaged, then K content of soils from 1911 to 1971 are very similar. The 1981 and 1984 samples contain considerably less total K. These results agree with Dubetz and Dudas (1981) who suggested that the Rotation U plot is operating under a K deficit.

The total K Contents of the 15 to 30 cm depth are also variable (Figure 15). In the unfertilized half of the plot there is an overall increase in total K between 1911 and 1961 followed by a steady decline in total K content between 1961 and 1984. The fertilized half of the plot starts with

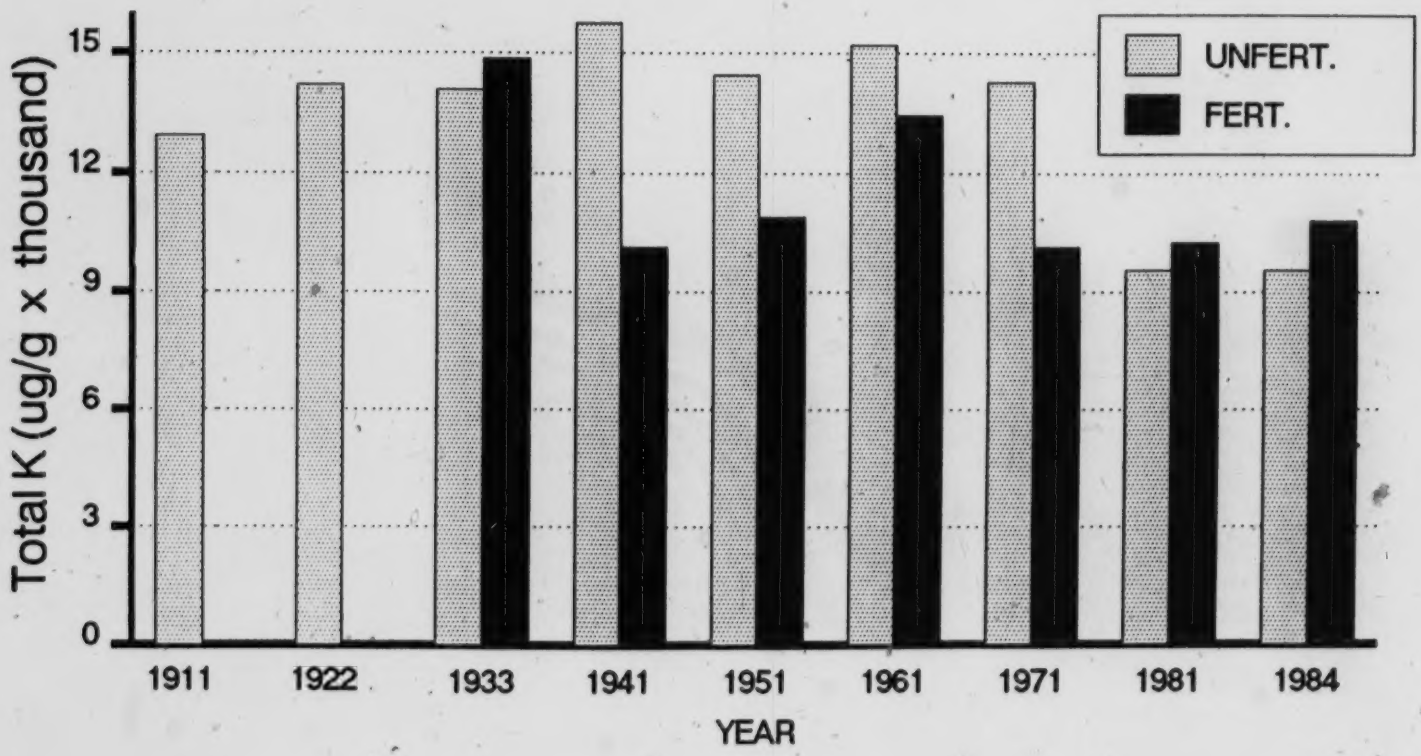

Figure 14. Content of total K in 0-15 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

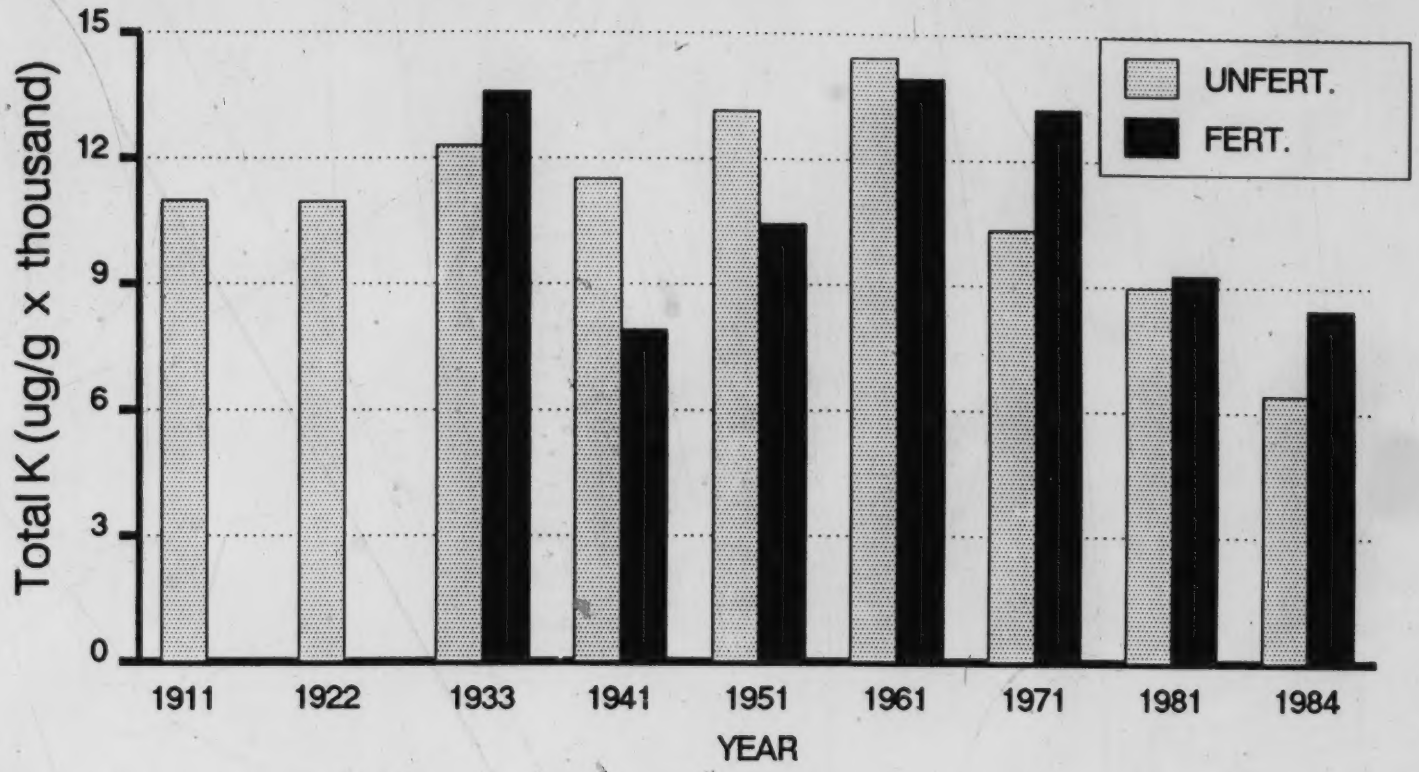

Figure 15. Content of total K in 15-30 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

a decline to the 1941 level. The remaining samplings indicated that the K levels of the fertilized section resemble the pattern taken by those of the unfertilized section. The similarity in the behaviour of the two plot sections was to be expected because there is no K added with the fertilizer so that K is being added only in manure and irrigation water and possibly by accretion of drift soil. All of these sources are added to both halves of the plot equally.

From the initial level of 1911, the total K content of the unfertilized plot section showed an increase over the first 30 years. Manure was probably the main source of additional K, although a small amount was being added in the irrigation water. Accreted topsoil would add K to the soil surface. Also, some K in soluble form may be moving up and down through the soil profile by capillary action, following fluctuations in the water table. The fluctuations in total K content are the result of the contribution of many factors. The soluble forms of K are extremely variable, especially in the surface soil, and reflect K additions, plant removal of K, and the effect of water table movements and irrigation practices.

The exchangeable K levels interact with soluble K levels, the organic matter content and clay levels in complex interactions. Both exchangeable and soluble K are part of the total K content. The most striking aspect of the total K content is the magnitude of the decrease from 15212 ug/g in 1961 to 9568 in 1984 in 0-15 cm depth, but a

proportion of this decrease is likely due to sample variability.

The Rotation U plot system is operating under a K deficit. The inputs in manure and irrigation water are falling short of removal by plants and through leaching. Dubetz and Dudas (1981) calculated the K deficit to be 60.26 kg.ha-1.yr-1.

There is no indication of K deficiency in the crops of the Rotation U plots, although uptake of K by alfalfa is very high. There are few reports of responses to K fertilizer in Southern Alberta.

6. Total S

The total S content of the surface soil stayed fairly constant from 1911 to 1941 (Figure 16). The sampling of 1951 indicated a substantial rise in total S content for both the fertilized and unfertilized section of the plot. The 10 years preceding the 1951 saw the application of manure on 3 occasions: 1944, 1946, and 1950. Three applications of manure is unusual for the 10 year rotation and came about during the 1941-1951 decade because of management changes. The high rate of manure application probably allowed a temporary accumulation of S in the soil immediately prior to the 1951 sampling. In the following decade, manure was applied only in 1956, so that by 1961 the total S values had declined to a level similar to those of 1911 to 1941, and remained fairly constant for the 1971, 1981, and 1984 samples.

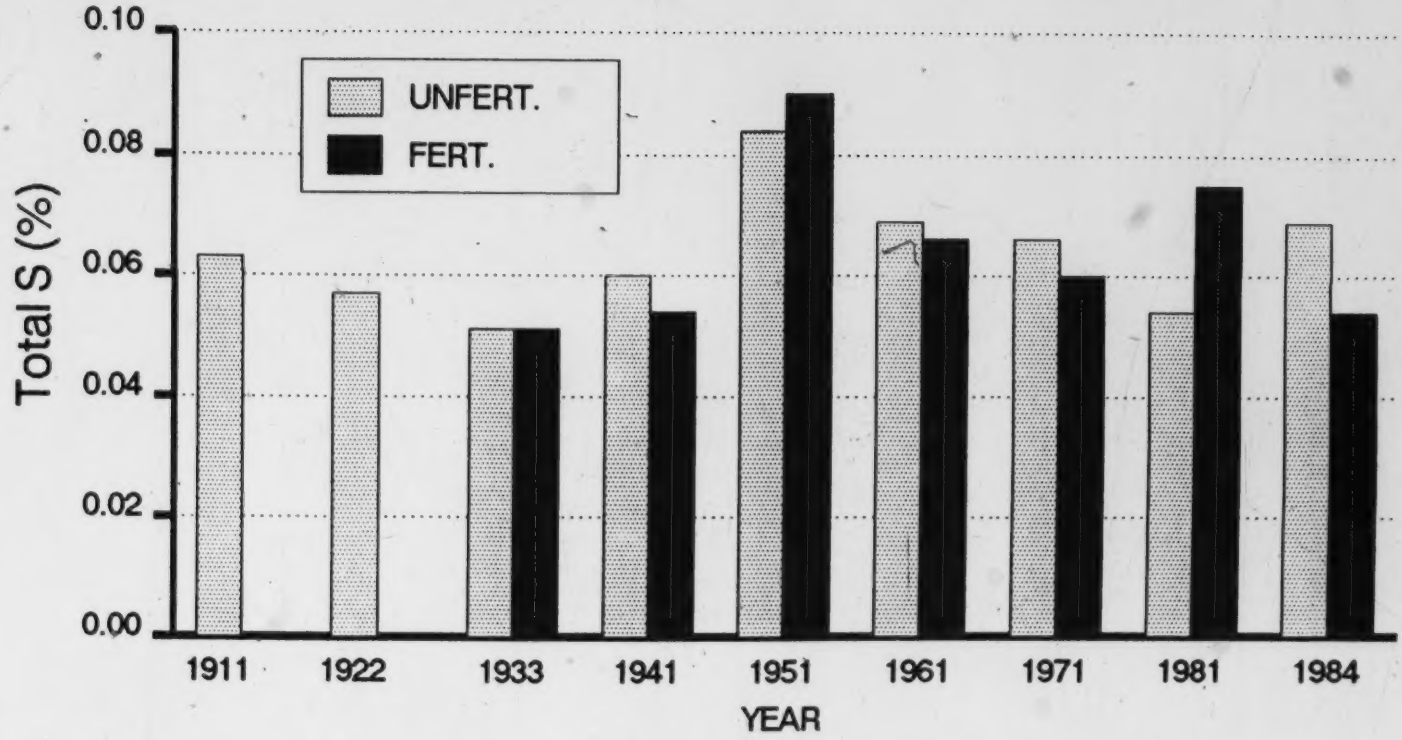

Figure 16. Content of total S in 0-15 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

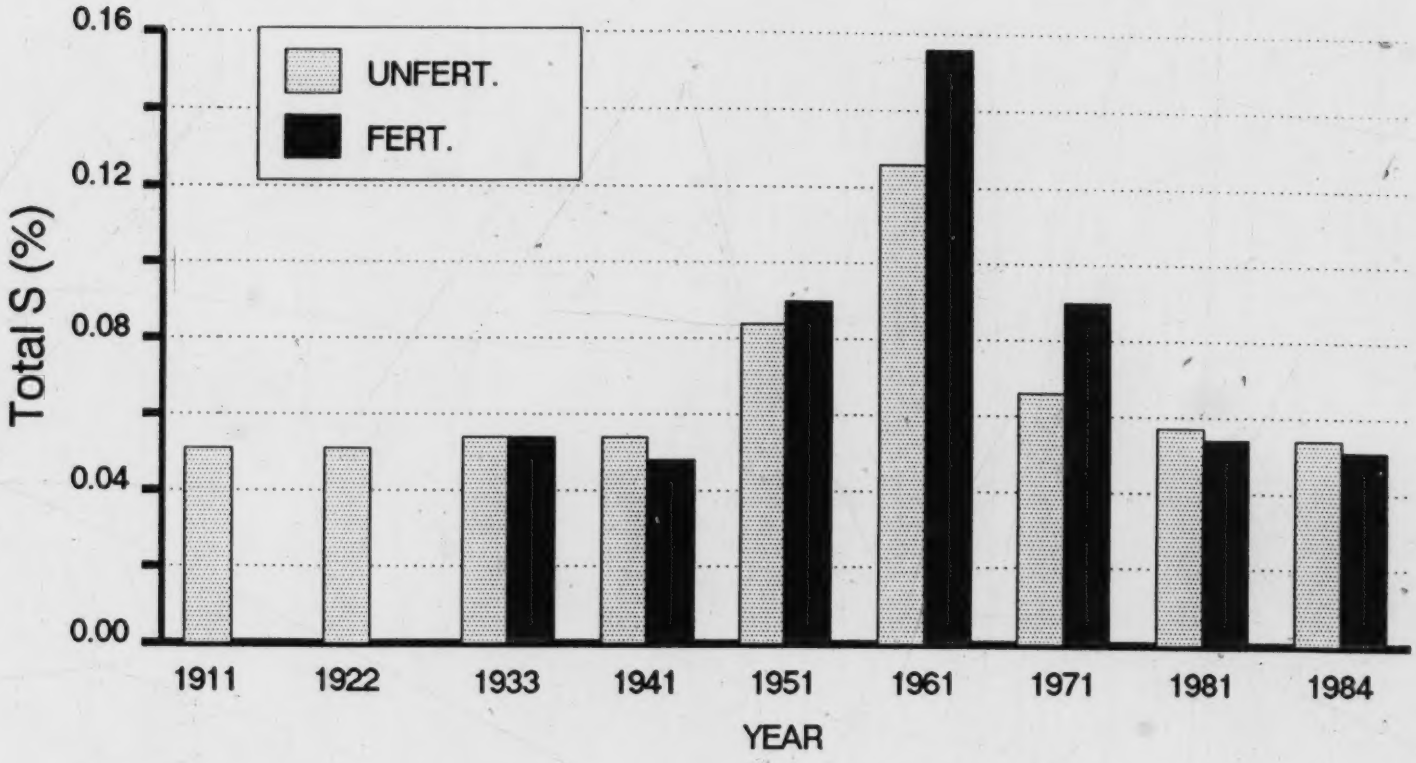

Figure 17. Content of total S in 15-30 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

The total S content of the 15-30 cm depth (Figure 17) follows a similar pattern except that the peak is displaced 10 years to the 1961 sampling, as the lower depth is slower to react to changes in management. Tillage operations may also have reached deeply enough into the soil to bring up S from depth. The S values declined as soluble S forms were leached away after installation of the sprinkler irrigation system in 1967.

With the exception of the 1951-61 spike in total S content, the relatively constant pattern of total S content follows the constancy of the organic matter contents.

This similarity is expected because 95-97% of S is estimated to be attached to organic matter particles (McLaren and Swift, 1977).

In a study of a series of soils in Scotland, McLaren and Swift (1977) stated that organically bound sulphur is the predominant form, with inorganic forms accounting for only a few percent of the total. Cultivated soils are expected to be lower in total S than undisturbed soils as cropping and cultivation bring about mineralization of organic matter and conversion to sulphate which is then available to plants (McLaren and Swift, 1977).

For the past seventy three years the net levels of total S on Rotation U have changed little. There is still an abundance of S available for plant growth. At the current rate of decrease it will be many decades before sulfur fertilization is required.

7. Total Calcium and Magnesium

From 1911 to 1933, the level of total Ca in the surface 15 cm of the unfertilized half of Plot 5 of Rotation U increased (Figure 18). A slight decline to the value of the 1941 sampling was followed by successive increases in total Ca content to 1961 where a small decline to the 1971 value is again followed by successive increases in 1981 and 1984. The fertilized half of the plot shows fluctuations in total Ca levels with an overall increase in the 1984 sample content of total Ca over the value of the 1933 sampling.

Figure 19 shows the temporal fluctuations in total Ca content of the 15 - 30 cm depth of Plot 5. At this depth there is also an overall increase in total Ca of both fertilized and unfertilized sections of the plot in 1984 compared to initial samplings. Although spatial variability in the field somewhat obscures the trend, there is an overall rise in the total Ca contents of both the surface soil and the 15-30 cm depth.

McKeague et al (1979) found Ca contents ranging from 0.50 to 2.75% in soils of the Canadian plains (surface horizons). The Ca content of Rotation U soils was similar.

The content of Mg is shown in Table 9. The levels of Mg in the plot soils have also shown an increase over 75 years but this rise is not nearly as dramatic as that for Ca. Magnesium content of Rotation U surface soil ranges from 0.64 to 0.92%, which is very similar to the range of 0.55 to 0.93% found by McKeague et al (1979).

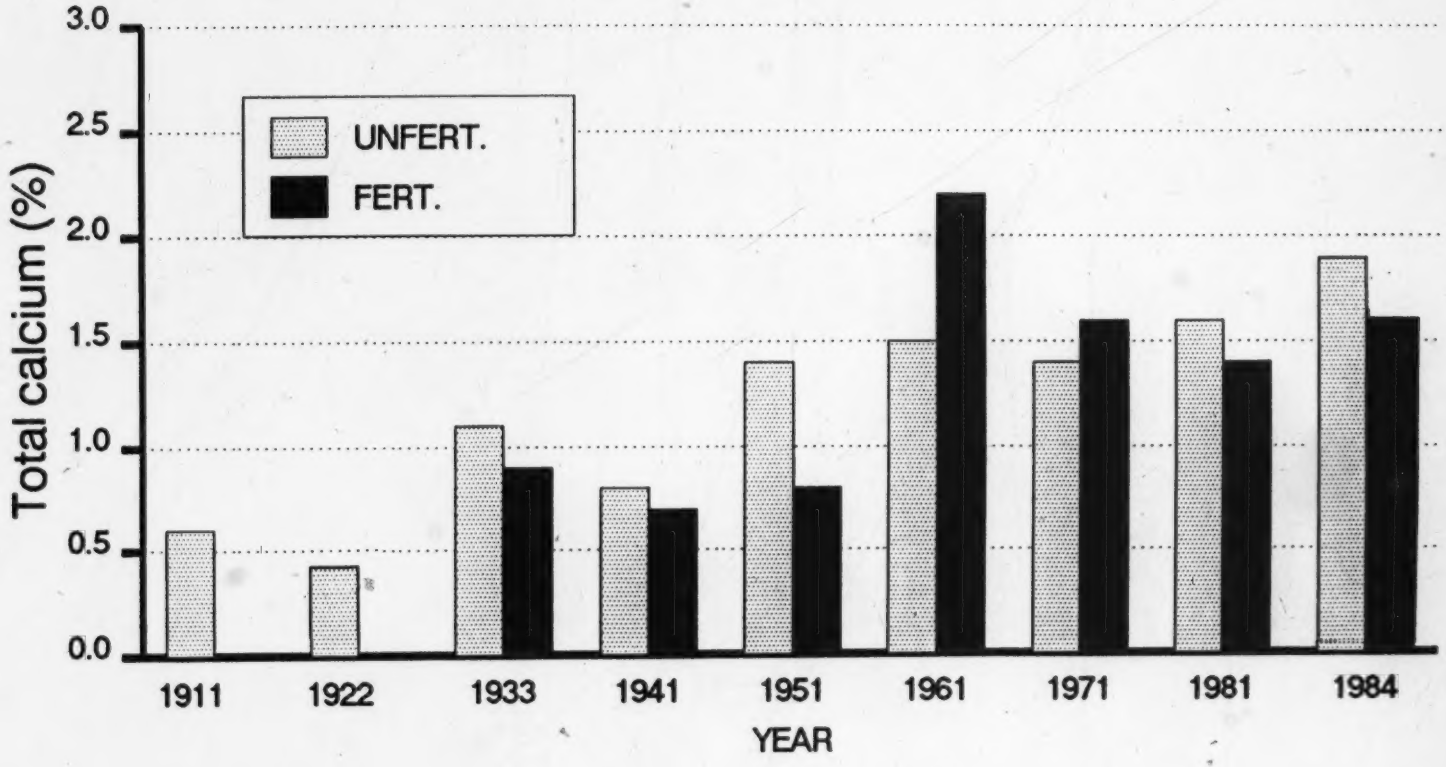

Figure 18. Content of total Ca in 0-15 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

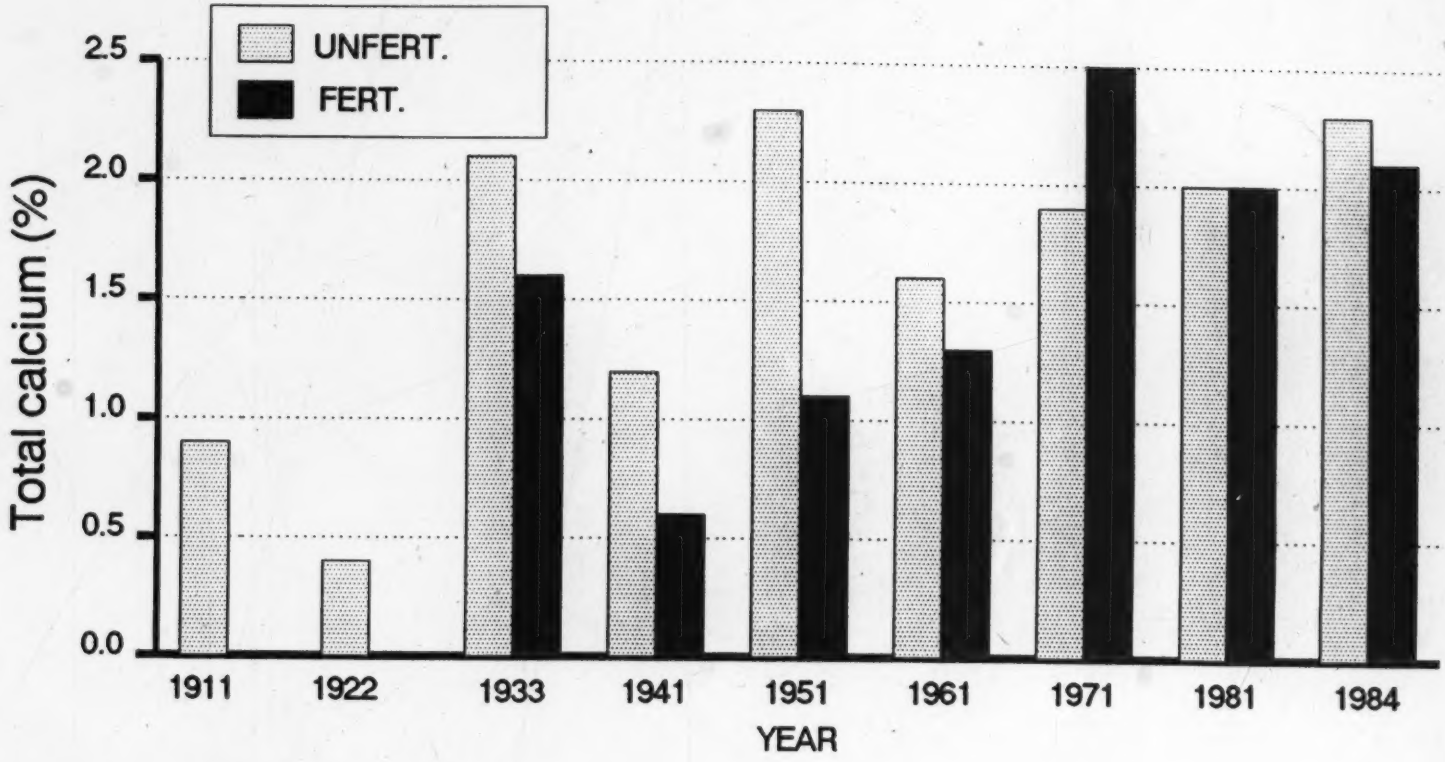

Figure 19. Content of total Ca in 15-30 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

The main sources of Ca and Mg are carbonate minerals, fertilizer, manure, and irrigation water. Some Ca and Mg taken up by crops was returned when grain stubble, beet tops, or alfalfa were plowed under. Accreted calcareous soil likely contributed to the increase in total Ca and Mg. Some amounts of both elements were brought up by cultivation. The lime layer could be reached by plowing after some topsoil had eroded, allowing portions of the lime layer to be incorporated into surface soil.

Although both cations show an overall increase, the individual samplings indicate considerable fluctuation in the levels of total Ca and total Mg in the soil. The fluctuations are partially the result of the sporadic nature of the inputs in conjunction with the timing of sampling.

The total Ca value of each soil sample includes soluble Ca, exchangeable Ca and mineral Ca, which at this pH (7.0 - 8.0) is mainly $CaCO_3$ and some $CaSO_4 \cdot 2H_2O$. The amount of $CaCO_3$ far exceeds the other forms of Ca, particularly in the 15 to 30 cm depth. Figure 7, which shows the levels of $CaCO_3$ in the 15 to 30 cm depth is very similar in pattern to Figure 19 which depicts total Ca levels for the same depth, suggesting that the contribution of soluble exchangeable, and mineral forms of Ca to the total is very small. Similarities in pattern are not so noticeable for the surface soil because soluble and exchangeable Ca are added to the surface with amendments and accreted soil.

Table 9. Content of total Mg (%) of Rotation U plot 5 soils from 1911 to 1984 (Detection Limit = 0.05%).

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth(cm)									
Unfertilized	0 - 15	0.64	0.59	0.77	0.57	0.90	0.53	0.77	0.79	0.71
	15 - 30	0.86	0.50	0.75	0.81	0.67	0.82	1.00	0.97	0.98
	30 - 60						1.80	1.40	1.60	
	60 - 90						1.70	2.20	2.20	
	90 -120								2.30	
	120 -150								1.90	
	150 -180								1.50	
Fertilized	0 - 15			0.69	0.52	0.65	0.92	0.76	0.84	0.80
	15 - 30			0.78	0.67	0.83	0.84	0.83	0.87	0.83
	30 - 60						1.50	1.60	1.60	
	60 - 90						2.20	2.20	1.90	
	90 -120								2.20	
	120 -150								1.70	
	150 -180								1.70	

8. Soluble Salts

The levels of soluble salts of Na, K, Ca, and Mg are very sensitive to environmental changes such as irrigation, fluctuations in the height of the water table, and manure and fertilizer applications (Table 10). As expected, the levels of soluble salts fluctuate widely over time and with depth, dependent on recent occurrences of fertilization, irrigation, or soil deposition. The only similarity is in the decline in recent years of all soluble salts to levels near or lower than 1911 values. Most reduction has taken place since 1951 for Ca and since 1961 for Na, and 1971 for Mg and K. The change in irrigation technique is probably partly responsible for removal of soluble salts through leaching, particularly in the last 20 years.

9. Exchangeable Cations

Table 11 shows the soil content of exchangeable cations. Exchangeable Na is quite low throughout the history of the plot. Fertilized and unfertilized areas are very similar. There is little Na in fertilizer and less than 1 me/l in the irrigation water (Lethbridge Research Station, unpublished data). The only significant source of Na is manure applications and these treatments are not contributing any noticeable amount of Na to the plot.

Exchangeable K levels are very stable over time and with depth in spite of the marked decreased in total K. Less available forms of K are being mobilized to maintain the exchangeable (readily available) levels of K. As a result,

Table 10. Content of soluble salts (ug/g) in Rotation U plot 5 soils from 1911 to 1984.

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Na										
Unfertilized	0-15	24	44	25	20	45	67	44	24	17
	15-30	36	31	25	23	45	135	76	40	15
	30-60						68	112	70	
	60-90						173	108	96	
Fertilized	0-15			47	22	46	63	56	27	17
	15-30			26	24	43	124	140	51	16
	30-60						185	167	95	
	60-90						166	157	126	
K										
Unfertilized	0-15	57	71	30	67	60	31	82	49	38
	15-30	72	39	31	38	41	32	44	30	29
	30-60						34	24	52	
	60-90						31	25	24	
Fertilized	0-15			52	55	55	68	55	38	40
	15-30			27	45	32	46	31	26	42
	30-60						25	26	20	
	60-90						24	26	24	
Ca										
Unfertilized	0-15	280	469	600	351	486	219	212	217	166
	15-30	274	241	480	322	504	514	302	230	230
	30-60						331	505	535	
	60-90						423	262	194	
Fertilized	0-15			637	278	446	232	249	190	178
	15-30			454	262	407	661	474	225	249
	30-60						663	403	336	
	60-90						227	280	267	
Mg										
Unfertilized	0-15	35	102	71	50	65	42	111	64	33
	15-30	31	60	44	37	66	110	57	32	28
	30-60						85	120	102	
	60-90						218	112	104	
Fertilized	0-15			79	46	73	69	45	52	28
	15-30			40	42	71	122	116	77	36
	30-60						273	117	105	
	60-90						133	112	116	

Table 11. Content of exchangeable cations (cmol/kg) of Rotation U plot 5 soils from 1911 to 1984.

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Na										
Unfertilized	0-15	0.04	0.04	0.05	0.04	0.06	0.11	0.08	0.05	0.05
	15-30	0.04	0.04	0.04	0.04	0.07	0.12	0.10	0.07	0.05
	30-60						0.07	0.06	0.08	
	60-90						0.12	0.08	0.07	
Fertilized	0-15			0.06	0.05	0.06	0.09	0.08	0.06	0.05
	15-30			0.04	0.04	0.06	0.10	0.10	0.08	0.05
	30-60						0.10	0.05	0.08	
	60-90						0.12	0.06	0.09	
K										
Unfertilized	0-15	0.60	0.53	0.52	0.86	0.50	0.57	0.58	0.67	0.56
	15-30	0.49	0.37	0.41	0.56	0.39	0.40	0.42	0.47	0.44
	30-60						0.15	0.19	0.20	
	60-90						0.15	0.16	0.17	
Fertilized	0-15			0.50	0.73	0.48	0.52	0.55	0.62	0.48
	15-30			0.34	0.51	0.41	0.37	0.39	0.42	0.39
	30-60						0.19	0.20	0.20	
	60-90						0.10	0.19	0.19	
Ca										
Unfertilized	0-15	14.06	11.78	18.71	18.44	20.65	23.29	21.86	22.86	21.32
	15-30	16.03	13.09	25.95	21.90	24.42	25.57	24.09	23.19	23.93
	30-60						20.42	24.58	21.99	
	60-90						21.94	19.32	20.99	
Fertilized	0-15			19.36	15.23	18.96	22.90	23.40	22.91	20.30
	15-30			23.33	15.85	23.91	24.82	25.55	23.69	21.36
	30-60						23.33	22.22	24.54	
	60-90						20.99	21.93	20.14	
Mg										
Unfertilized	0-15	3.03	3.35	2.57	3.71	3.38	4.69	4.68	4.34	4.31
	15-30	1.65	3.02	2.56	3.24	3.73	5.17	5.38	4.64	4.76
	30-60						5.19	5.47	5.94	
	60-90						8.16	6.18	7.28	
Fertilized	0-15			2.58	3.30	3.48	4.98	5.34	5.38	4.06
	15-30			2.31	3.32	4.34	5.18	5.73	5.53	4.79
	30-60						7.43	6.17	6.52	
	60-90						8.66	7.29	7.39	

plants are not showing K deficiencies. There is still a large amount of K remaining in relatively unavailable forms. It will be a considerable time before depletion of these forms of K permits a decline in exchangeable K.

Exchangeable Ca is high and is apparently increasing with time. Fertilizer is supplying a small amount of Ca to the south half of the plots but its contribution is negligible compared to the large Ca addition from irrigation and accretion of soil high in $CaCO_3$. The fertilized and unfertilized plot sections show nearly identical rises in the exchangeable Ca level. Calcium has always been the dominant cation in this soil, but the proportion of Ca is increasing. (Free $CaCO_3$ is influencing the suite of cations on the exchange complex).

These soil samples contain free $CaCO_3$ and as a result the measurement for exchangeable Ca is invalid as the extracted Ca includes both the exchangeable Ca as desired as well as free Ca^{+2} from $CaCO_3$. As overall CEC is rising (Figures 20 and 21) it is reasonable to expect that exchangeable Ca is rising proportionately. This analysis of exchangeable Ca cannot be used to quantify the increase because of the inclusion of free Ca.

Exchangeable Mg has also increased with time (Table 11). Since 1951, the exchangeable Mg level on the fertilized section of the plot has been consistently higher than the unfertilized half. Manure, fertilizer, irrigation water and accretion of soil high in carbonate have all contributed to

the rise in exchangeable Mg. From a comparison of the exchangeable cation levels, salinity is not a concern. The Na level is very low compared to the contents of Ca and Mg.

There is also free $MgCO_3$ in these soil samples and therefore the exchangeable Mg value is actually the sum of dissolved Mg from $MgCO_3$ as well as true exchangeable Mg. The rise in total CEC would predict a rise in exchangeable Mg, but again the amount cannot be quantified.

10. Total Cation Exchange Capacity

Figure 20 shows the total CEC values for the surface 15 cm of Rotation U plot 5. Using the difference between the fertilized and unfertilized sections of the plots as an indicator of variability, it can be seen that any change between sampling dates could be accounted for by spatial variability in the field. The total CEC has been steadily maintained over 73 years. In Figure 21 which depicts total DEC values for the 15-30 cm depth, there is less variation. The CEC has remained steady over the history of the plots.

The CEC is a function of amount and type of clay, and the amount of organic matter in the soil. As the net organic matter content has remained fairly steady over 73 years, the CEC could be expected to also remain at a constant level. The trend toward increasing clay contents of the Rotation U plot would contribute to an increase in CEC, but the dominant effect of the organic matter content on CEC almost completely obscures any rise in CEC caused by increasing clay content.

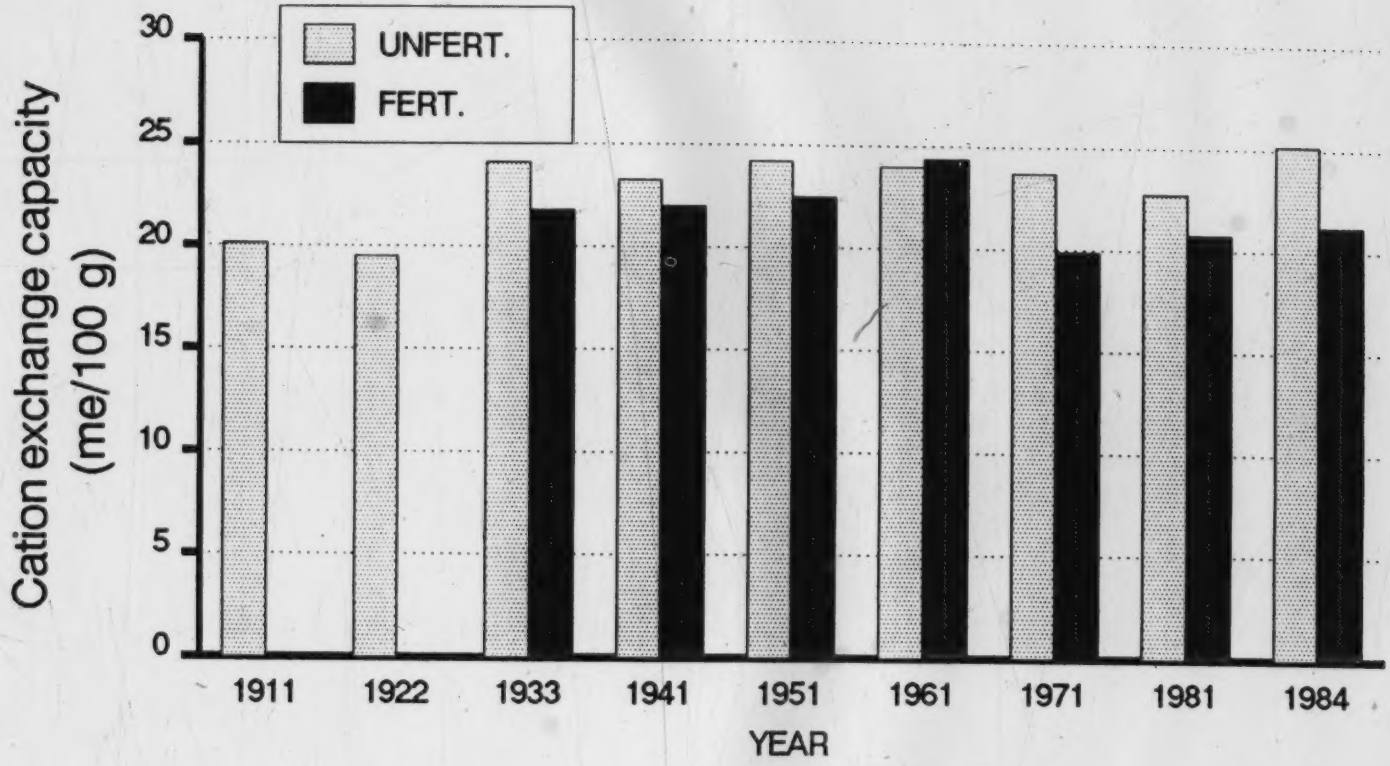

Figure 20. Total cation exchange capacity of 0-15 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

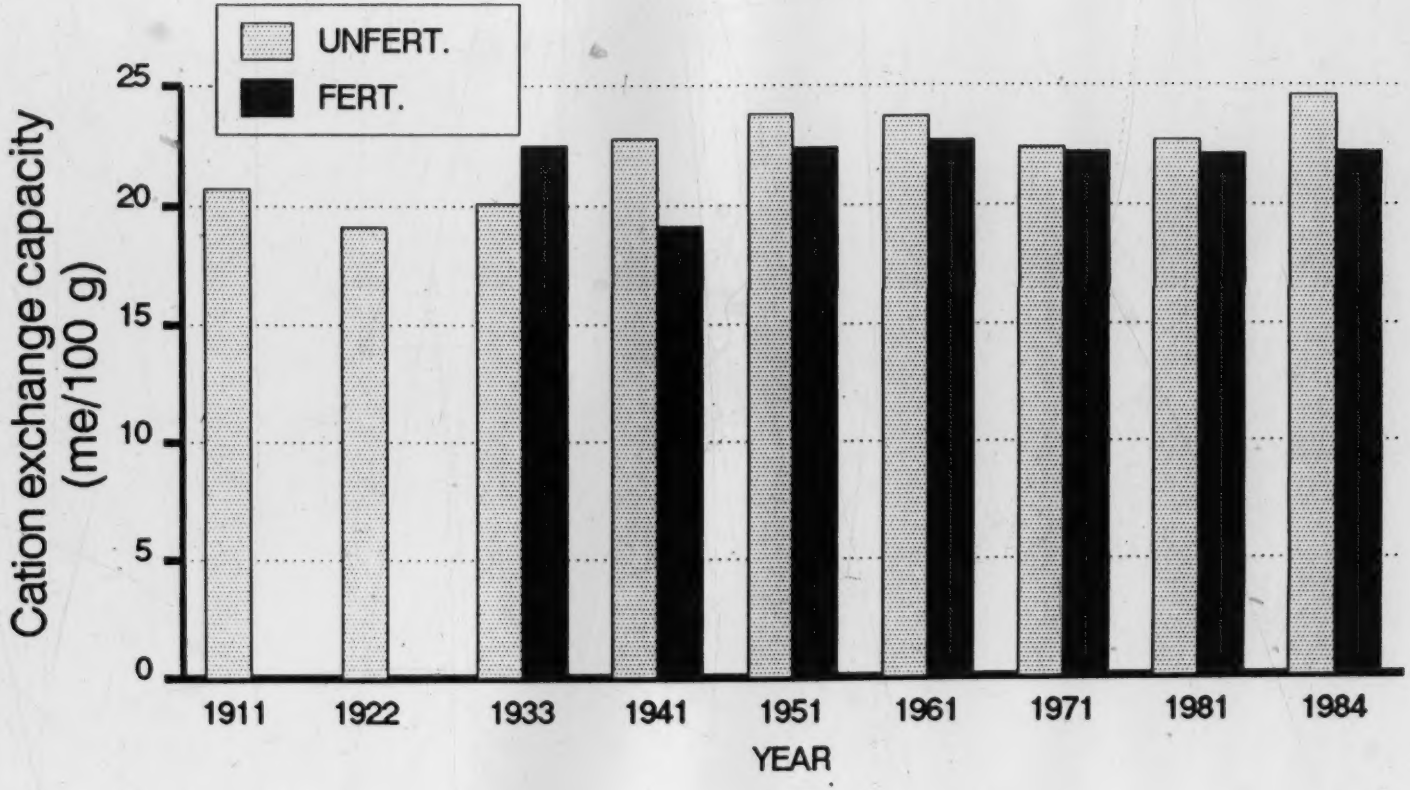

Figure 21. Total cation exchange capacity of 15-30 cm. depth of Rotation "U" Plot 5 from 1911 to 1984.

11. Trace Elements

Table 12 shows a list of trace elements for which the concentration in the soils analyzed was too low to be detected by neutron activation analysis. The detection limit for each element is included. The only known nutrient on the list is Mo. Although the crops grown on Rotation U show no sign of Mo deficiency and there have been no reports of response to Mo fertilizer application with this low level of Mo, the possibility of a deficiency exists. The level of Mo in the plot soils should be monitored by a more sensitive method than neutron activation analysis. Plant tissue from Rotation U crops could be tested for Mo to assess deficiency.

Table 13 shows a further list of trace elements. The concentrations of these elements in the plot soils was virtually unchanged by time and management practices. The detection limit for each element is included, as well as the ranges of concentration of the elements in the 0 - 15 cm depth. Complete tables of the results over 73 years appear in the Appendix. Concerns regarding toxic accumulations with time caused by phosphate fertilizer application appear to be unfounded in the case of these elements. The level of phosphate fertilizer application is quite low compared to rates used by many Alberta farmers and the frequency of application (twice in 10 years) is also very low. Table 14 lists the fertilizer content of the same elements. The triple superphosphate was only used for about five years so

Table 12. Elements in soil samples which occurred at or below INAA detection limits.

Element	Detection limit
Gold	5 ng/g
Indium	200 ng/g
Iodine	5 ug/g
Molybdenum	2 ug/g
Nickel	50 ug/g
Selenium	0.5 ug/g
Silver	2 ug/g
Strontium	100 ug/g
Tantalum	0.5 ug/g
Tungsten	1 ug/g

Table 13. Content of elements in soils which appeared unchanged during the history of Plot 5.

Element	Detection limit	Range (0-15cm depth)
Aluminum	0.01 %	4.82 - 5.06 %
Antimony	0.1 ug/g	0.9 - 1.0 ug/g
Arsenic	1 ug/g	8 - 9 ug/g
Barium	20 ug/g	590 - 640 ug/g
Boron	0.5 ug/g	36 - 44 ug/g
Bromine	0.5 ug/g	2.2 - 3.3 ug/g
Cerium	1.0 ug/g	42 - 45 ug/g
Cesium	0.2 ug/g	2.9 - 3.4 ug/g
Chlorine	20 ug/g	50 - 110 ug/g
Chromium	0.5 ug/g	45 - 53 ug/g
Cobalt	0.1 ug/g	5.9 - 6.9 ug/g
Dysprosium	0.5 ug/g	3.8 - 4.5 ug/g
Europium	0.05 ug/g	0.59 - 0.83 ug/g
Hafnium	0.2 ug/g	5.4 - 6.3 ug/g
Iron	0.005%	1.80 - 1.98 %
Lanthanum	0.1 ug/g	22.9 - 24.7 ug/g
Lutetium	0.01 ug/g	0.29 - 0.31 ug/g
Manganese	0.1 ug/g	330 - 400 ug/g
Neodymium	3 ug/g	16 - 20 ug/g
Rubidium	10 ug/g	60 - 70 ug/g
Samarium	0.01 ug/g	3.54 - 3.83 ug/g
Scandium	0.01 ug/g	6.7 - 7.2 ug/g
Sodium	30 ug/g	5400 - 5900 ug/g
Terbium	0.1 ug/g	0.4 - 0.5 ug/g
Thorium	0.2 ug/g	6.1 - 6.7 ug/g
Titanium	100 ug/g	2100 - 2600 ug/g
Uranium	0.1 ug/g	1.8 - 2.3 ug/g
Vanadium	1 ug/g	70 - 82 ug/g
Yttberbium	0.05 ug/g	1.80 - 1.95 ug/g
Zinc	5 ug/g	90 - 110 ug/g

Table 14. Elemental content of two fertilizers used on Rotation U plots.

Element	Detection limit		Triple superphosphate 0-43-0		Ammonium phosphate 11-48-0	
Aluminum	0.01	%	0.49	%	0.97	%
Antimony*	0.1	ug/g	1.2	ug/g	3.0	ug/g
Arsenic	1	ug/g	3	ug/g	8	ug/g
Barium	20	ug/g	200	ug/g	<100	ug/g
Boron	0.5	ug/g	22	ug/g	30	ug/g
Bromine	0.5	ug/g	1.5	ug/g	2.1	ug/g
Calcium*	0.2	%	20.4	%	2.5	%
Cerium	1	ug/g	54	ug/g	28	ug/g
Cesium	0.2	ug/g	0.6	ug/g	0.8	ug/g
Chlorine	20	ug/g	<40	ug/g	<40	ug/g
Chromium*	0.5	ug/g	44	ug/g	90	ug/g
Cobalt	0.1	ug/g	1.8	ug/g	4.2	ug/g
Dysprosium*	0.5	ug/g	11.2	ug/g	7.6	ug/g
Europium*	0.05	ug/g	1.09	ug/g	0.85	ug/g
Gold	5	ng/g	<5	ng/g	<5	ng/g
Hafnium	0.2	ug/g	3.4	ug/g	0.3	ug/g
Indium	200	ng/g	<200	ng/g	<200	ng/g
Iodine*	5	ug/g	7	ug/g	22	ug/g
Iron	0.005	%	0.435	%	1.250	%
Lanthanum	0.1	ug/g	46.4	ug/g	25.8	ug/g
Lutetium*	0.01	ug/g	1.14	ug/g	1.36	ug/g
Magnesium	0.05	%	0.14	%	0.62	%
Manganese	0.1	ug/g	140	ug/g	370	ug/g
Molybdenum	1	ug/g	Interference		Interference	
Neodymium*	3	ug/g	40	ug/g	21	ug/g
Nickel*	50	ug/g	90	ug/g	80	ug/g
Rubidium	10	ug/g	<10	ug/g	10	ug/g
Samarium*	0.01	ug/g	6.82	ug/g	3.30	ug/g
Scandium	0.01	ug/g	3.8	ug/g	6.8	ug/g
Selenium	0.5	ug/g	<1.5	ug/g	<1.5	ug/g
Silver	2	ug/g	<2	ug/g	2	ug/g
Sodium	30	ug/g	1100	ug/g	2600	ug/g
Strontium	100	ug/g	300	ug/g	100	ug/g
Tantalum	0.5	ug/g	<0.5	ug/g	<0.5	ug/g
Terbium*	0.1	ug/g	1.2	ug/g	0.8	ug/g
Thorium	0.2	ug/g	3.7	ug/g	7.4	ug/g
Titanium	100	ug/g	500	ug/g	100	ug/g
Tungsten	1	ug/g	1	ug/g	1	ug/g
Uranium*	0.1	ug/g	80.7	ug/g	168	ug/g
Vanadium	1	ug/g	62	ug/g	140	ug/g
Ytterbium*	0.05	ug/g	5.75	ug/g	6.63	ug/g
Zinc	5	ug/g	64	ug/g	70	ug/g

*Higher than soil.

the contribution of its contaminant trace elements is very small. The ammonium phosphate has now been in use for over 45 years. It can be seen that fertilizer levels of most of the trace elements are very low, often near or below the detection limit. Of the 42 elements listed, only 14 (shown by *) are more concentrated in the fertilizer than in the soil. These 14 elements have the greatest potential to accumulate. In viewing the results of the soil analyses, none of the elements has either increased or declined in concentration. The amounts added as contaminants in the fertilizer are not causing toxic accumulations. Trace elements are also added through manure application and irrigation. Again, concentrations are apparently insufficient to cause increases in element concentrations. The lack of deficiency symptoms and lack of response to micronutrient fertilizer suggests that micronutrient deficiencies are not developing. The small amounts of Zn, Fe, Mn, and B in the amendments are being balanced by plant uptake. The possibility of deficiency does exist though with the continuing increase in pH. The micronutrients Zn, Cu, Fe, Mn, and B become less available at high pH. Tests for available micronutrient levels are not yet standardized or correlated with plant response but plant tissue analysis will detect micronutrient deficiencies. The continuing high yield of Rotation U crops and lack of deficiency symptoms indicate that micronutrient deficiencies are not occurring to any great extent at present.

None of the trace elements showed any indication of accumulation in the soil even though phosphate fertilizer, manure, and irrigation water are supplying some trace elements to the plots. The amounts of trace elements added are likely balanced by the total removed by plant uptake, leaching and erosive losses.

Tables 24 to 53 of the Appendix show detailed trace element data for all elements which could be detected by neutron activation analysis.

Aluminum

The level of Al in the plot 5 soils has remained between 4.82 and 5.06% Al for seven decades (Table 24). This value is lower than the range of 10.4 to 28.97% Al reported in soils by Wolfenden (1965), but is identical to the 4.8 - 5.1% found by McKeague et al (1979).

The 0-43-0 fertilizer contained 0.49% Al, and the 11-48-0 contained 0.97%. Although this is a fairly high content, it appears to have had little effect on the Al levels of the plots. These levels have remained constant for 70-73 years. The high soil pH is likely keeping the Al virtually completely insoluble and unavailable. Aluminum toxicity is not a concern on the high pH soils of Rotation U.

Antimony

The Rotation U soils maintained a steady net content of Sb of 0.9 - 1.0 ug/g for 73 years (Table 25). This is lower than the 5 ug/g Sb reported by Levinson (1974). Phosphate fertilizer contains 1 - 10 ug/g Sb (Swaine, 1962). The

triple superphosphate contained 1.2 ug/g and the ammonium phosphate 3.0 ug/g Sb. Although these amounts are slightly higher than the content of the plot soils, their addition has had little effect.

Arsenic

The soils of the Rotation U plots were found to have 8 - 9 ug/g As (Table 26). This amount is reasonable considering the geological heritage of the plots, and is fairly close to the 3.9 ug/g found by Dudas and Pawluk (1980) in a Dark Brown Chernozemic surface soil.

The 0-43-0 fertilizer contained only 3 ug/g As and the 11-48-0 only 8 ug/g As. The rather restricted use of fertilizer on the plots is supplying very little As to the soil. This should elminate any concern regarding the development of As poisoning from fertilizer contaminants. The danger of applying high amounts of As in P fertilizer does exist, as Swaine (1962) quotes As contents of trace to 1490 ug/g in phosphate fertilizers.

Arsenic is slightly depleted in surface horizons because of depletion in clay sized fractions (Dudas and Pawluk, 1980). This phenomenon was not noticeable in this study; the surface values were not significantly different from those at depth. The highest value attained, a surface sample, contained 9 ug/g As, while the deepest 3 depths from the comprehensive 1961 sampling all contained 7 ug/g As.

Arsenic has recently been established as an essential element for animals. The quantity required is very small,

and deficiencies are unlikely. With As, the major problem is the potential toxicity posed by excess quantities of As in soil which may be absorbed by plants and thereby passed on to animals, or soil ingested directly by grazing animals.

Barium

Barium in the soil of the Rotation U plots ranged from 590 to 640 ug/g (Table 27), well within the range reported by Levinson (1974) of 100 - 3000 ug/g. The Ba content of fertilizer, as reported by Swaine (1962) is extremely variable: 1 - 800 ug/g Ba. The triple superphosphate of Rotation U was found to contain 200 ug/g Ba. The ammonium phosphate tested at less than 100 ug/g Ba. Farmyard manure, as noted by Swaine (1962) apparently contained no Ba. The lack of Ba in manure and the low content of Ba in fertilizer result in very low Ba inputs to the plots. As Ba is sparingly soluble and difficult to exchange, leaching losses are likely to be small. Most plants do not take up much Ba because of its toxicity. These factors all contribute to the stable levels of Ba in Rotation U soils over time.

Boron

The B content of the surface soil of Plot 5 remained between 37 and 44 ug/g in the unfertilized half of the plot and between 36 and 40 ug/g in the fertilized section. The B content changes very little with depth (Table 28). Total B in soil varies with the content of the parent material and extent of weathering. Boron levels have often been reported as 20 - 50 ug/g although a range of 1 - 270 ug/g has been

noted (Barber, 1984). Boron levels tend to be low in sandy soils, particularly those that have been leached (Sillanpaa, 1972;Barber, 1984). Soils containing high levels of clay and/or organic matter have higher B contents.

Boron requirements and B uptake by plants are extremely variable. Root crops and legumes are highest in requirements while cereals and hays are lowest. A healthy crop of barley may contain 2 to 4 ug B/g of ovendry material, wheat may contain 3 to 5 ug B/g, alfalfa 20 to 40 ug B/g, while sugar beet leaves contain 25 to 40 ug B/g. A deficient crop of alfalfa may contain only 7 to 19 ug B/g while a deficient sugarbeet crop contained only 13 to 20 ug B/g (Sillanpaa, 1972 and Sauchelli, 1969).

Sillanpaa (1972) notes that the annual removal of B from soil varies considerably with soil B content, plant species, and yield. The plowing under of the sugarbeet tops, grain stubble, and part of the alfalfa crops returns B to the soil, so crop removal of B is decreased.

The B content of the phosphate fertilizers used on Rotation U could be quite variable, considering the values reported by Swaine (1962). Examples of superphosphate B content range from 4 to 100 ug B/g, triple superphosphate contained 24 - 800 ug B/g, while manure contained 3 to 50 ug B/g (Swaine, 1962). The 0-43-0 used on Rotation U contained 22 ug/g and the 11-48-0 contained 30 ug/g.

In Rothamsted the B content of plots cultivated for 100 years was stable (Jones et al, 1987). Sillanpaa (1974)

indicates that manure has a low B content; ranging from 1 to about 8 ug/g, and averaging 2 - 4 ug/g. In one tonne of fresh material, this would correspond to 2 to 4 grams of B. In comparing plant uptake with the fertilizer and manure contents, it is obvious that the additions of fertilizer and manure cannot keep up with the removal of B by crops. Yet no deficiency symptoms are developing on the crops of Rotation U, even though the alfalfa and sugarbeets are heavy users. The B requirements of small grain crops are so low that B deficiency symptoms are extremely rare under field conditions (Sillanpaa, 1972).

Boron resides principally in the clay mineral fraction, and high concentrations of B are found in shales, particularly those of marine origin. It is likely then that the clay materials eroding from areas west of Lethbridge and collecting on Rotation U plots are enriched in B to the extent that the addition of B by deposition of clay, and applications of manure, fertilizer and irrigation water are balancing the removal by crops and leaching.

Bromine and Iodine

The Br content (Table 29) of the top 30 cm of Plot 5 of Rotation U ranges from 2.5 to 3.1 ug/g for the unfertilized half of the plot. The range is 2.2 to 3.9 ug/g Br for the fertilized half of the plot. For I, all soil levels are below the detection limit of neutron activation analysis which is 5 ug/g. These two halogens are present in low amounts and follow similar distribution patterns because of

similar geochemistry (Plant and Raiswell, 1983).

Iodine content of soil can be increased by fertilizer additions. Superphosphate contains 4.6 - 40.2 ug/g I (Swaine, 1962). Rotation U triple superphosphate contained 7 ug/g I and 1.5 ug/g Br. The ammonium phosphate contained 22 ug/g I and 2.1 ug/g Br. Manure may contain 0.04 - 1 ug/g I (Swaine, 1962). Manure applications appear to cause release of formerly unavailable soil I as opposed to merely contributing their own I content (Sauchelli, 1969). Although these contributions appear high compared to the soil content, no accumulations have been detected, probably because the very soluble I forms are being leached by irrigation and rainwater. Crop removal represents an insignificant loss.

Cesium

The Rotation U soils were found to contain 2.9 - 3.4 ug/g Cs in the top 15 cm (Table 31). About 3 ug/g Cs is contained in the earth's crust. Values of 5 ug/g in shale and 6 ug/g in soil are reported elsewhere (Levinson, 1974). Again, there is concern over Cs levels because Cs-137 is now the most abundant fission product of weapons testing. Its half-life is 30 years. Cesium is chemically similar to K and enters the food chain in a like manner.

There is widespread fixation of Cs in a nonexchangeable form in vermiculite and mica. As a result Cs has poor mobility in soil and is taken up by plants in small quantities (Reitemeier et al, 1967).

Fertilizer values were found to be 0.6 ug/g Cs for 0-43-0, and 0.8 ug/g Cs for 11-48-0. In comparison with soil levels, these additions are small. The immobility and low uptake of Cs result in very small losses of this element. That no accumulations of this element appear to be developing suggests that the inputs of Cs (stable or radioactive) are correspondingly tiny.

Chlorine

The Cl content (Table 32) of the Rotation U soils ranges from less than 50 ug/g to 80 ug/g in the top 30 cm, with one value (1984 unfertilized surface soil) reaching 110 ug/g. The detection limit is 20 ug/g so this variability is not significant and all the values from 1911 to 1984 can be considered to be the same. The fertilizer content is also low (less than 40 ug/g). There is little likelihood of a deficiency in the field. Chlorine is applied to soil in trace amounts in nearly all fertilizers, and in fairly substantial amounts in ammonium chloride and potassium chloride fertilizers. Significant amounts are also applied in manure treatments. Rainfall supplies measureable quantities of Cl (Sillanpaa, 1972). Rainfall, fertilizer contaminants, manure additions, and soil content likely will continue to supply the tiny amounts of Cl needed by crops on Rotation U.

Increasing amounts of organic matter and clay are not accompanied by detectable increased levels of Cl. The commonest form of Cl is the negatively charged Cl^- anion,

which is repelled by the negative charge contained on organic matter and clay colloids.

Chromium

The soils of Rotation U contained 47 -53 ug/g Cr (Table 33). In Rothamsted, 98 - 124 mg Kg^{-1} Cr was found in historical samples from long term plots (Jones et al, 1987). Levinson (1974) reports values of 5 - 1000 ug/g Cr, while McKeague et al (1979) indicate a range of 18 - 62 ug/g Cr for soils of the Canadian interior plains (surface horizons). The Cr values of the soils of Rotation U fit within this range. As Cr is a potentially toxic element, there is concern over its level in the environment. Soils formed over ultrabasic rocks may have very high natural levels of Cr. Pollution from mining and other industries may contribute significant quantities of Cr to the atmosphere, waters and soil. These circumstances do not affect the Lethbridge area.

Phosphate fertilizer Cr content ranges from trace to 1000 ug/g (Swaine, 1962). The fertilizers used on Rotation U contained rather low amounts. The 0-43-0 had 44 ug/g and the 11-48-0 90 ug/g Cr. While these values are higher than the soil levels, the fertilizer is not added in large enough quantities or frequently enough to permit development of accumulations. The net content of Cr is likely to remain fairly steady as most Cr compounds are insoluble and therefore immobile at the high pH of the plots, plant uptake is small, and inputs are minimal. At Rothamsted, Cr showed

no consistent changes over the term of the plot (Jones et al, 1987).

Cobalt

On Rotation U, the surface soils over 75 years varied little: 5.9 - 6.9 ug/g total Co (Table 34). This compares with 6.4 ug/g found by Dudas and Pawluk (1980) in the Ah horizon of a Dark Brown Chernozem. This level is expected for soils developed on glacial till in Alberta. McKeague et al (1979) noted higher Co values, ranging from 8 to 20 ug/g, in samples from the Interior Plains of Canada.

Fertilizers usually contain less than 10 ug/g Co (Swaine, 1962). The superphosphate used on Rotation U was typical, containing 4.2 ug/g total Co. It is likely that the manure and irrigation waters are supplying tiny amounts of Co to the plots. The quantities of Co added as well as the quantities removed are very small.

To this date, no accumulations of Co have been noted. Also no Co deficiency symptoms have ever been recorded in the crops of the Rotation U plots.

Gold

In both phosphate fertilizers and in Rotation U soils Au is below the detection limit of 5 ng/g. Gold is one of the least abundant elements in the earth's crust, averaging 0.004 ug/g. It is found at that level in granite and shale and at 0.005 ug/g in limestone (Levinson, 1974). Gold does not pose a health hazard, nor is it required as a nutrient by plants, animals, or man.

Hafnium

The soil content of Hf on the Rotation U plots ranges from 5.6 - 6.3 ug/g (Table 37). There appears to be little net change in Hf concentration over 73 years of cultivation. The original triple superphosphate contained 3.4 ug/g Hf and the ammonium phosphate contained only 0.3 ug/g, so these sources are not likely to increase the Hf concentration.

Indium

The detection limit of neutron activation analysis for In is 200 ng/g. The fertilizers and the soil samples are both below that level.

Iron

The surface 15 cm of the unfertilized half of Plot 5 Rotation U contain 1.83 to 1.98% Fe; the 15 - 30 cm depth averages slightly less, ranging from 1.79 to 1.88% Fe (Table 38). The fertilized half of the plot showed a range of 1.76 to 1.93% Fe in the surface soil and 1.72 to 1.91% Fe in the 15-30 cm depth. The content of Fe initially decreases with depth to 90 cm then levels begin to rise with further increments in depth.

In temperate soils, the total Fe usually ranges from one to five per cent, bound mainly in the clay and silt fractions (Sillanpaa, 1972). In their analysis of soils of the Canadian Plains, McKeague et al (1979) found 1.2 to 2.4% Fe. These results indicate that the Rotation U soils which contain 1.82-1.98% Fe fall into this range. The increase in clay content over time suggests that there should be a

corresponding increase in total Fe content. Iron is also being added in fertilizer. The triple superphosphate contained 0.435% Fe and the ammonium phosphate contained 1.250% Fe. Manure supplies approximately 0.05 Kg Fe/tonne (Swaine, 1962) while the irrigation water contains 0.30 mg Fe/L (Lethbridge Research Station, unpublished data) or 1.5 Kg Fe/ha/yr.

Although the Rotation U plots ar calcareous, with high pH and high levels of Ca, P, and antagonistic metals, Fe deficiency has never been reported. It is probable that there are sufficient soluble Fe-humates to supply crop needs.

Lanthanides

The lanthanides are a group of 15 metals beginning with lanthanum (atomic number 57) and ending with lutetium (atomic number 71). Neutron activation analysis provided data on the soil and fertilizer contents of some of these elements including: Ce, Dy, Eu, La, Lu, Nd, Sm, Tb, and Yb (See Tables 30, 35, 36, 39, 40, 42, 45, 47, and 52). All of the lanthanides were above the detection limit. There is little net change in the content of these selected lanthanides in the Rotation U soils over 73 years, even though fertilizer additions were in every case higher than the soil levels, in some instances markedly so. Soil concentrations of 40 ug/g La, 50 ug/g Ce, and 35 ug/g Nd are quoted by Essington and Mattigod (1985). These researchers mention that Lu is the least abundant lanthanide, but Lu occurs in

soils at higher concentrations than Ag, Be, Bi, Cd, or Mg. Therefore these ubiquitous elements do not deserve to be termed "rare earths" as they are not particularly rare. The lanthanides all have a similar atomic structure and a resultant similar geochemistry. They occur together in minerals.

Manganese

The Mn content of soil samples from the surface 15 cm of the unfertilized half of Plot 5 ranges from 330 to 400 ug Mn/g (Table 41). The Mn content of the soils at the 15 - 30 cm depth ranges from 330 to 380 ug Mn/g. The fertilized half of the plot shows very similar results with surface soils containing 360 to 390 ug Mn/g and the 15 - 30 cm depth soils containing 330 - 370 ug Mn/g. The surface soils contain slightly more Mn than the 15 - 30 cm depth but the surface receives larger inputs of Mn. The overall content of the top 30 cm ranges between 330 and 400 ug Mn/g. This is similar to the 230 ug Mn/g reported by Dudas and Pawluk (1980) for Brown Chernozems. Most of the surface soils of the Canadian plains studied by McKeague et al (1979) were found to contain 440 to 515 ug/g of Mn. The lowest value reported was 165 ug/g Mn and the highest was 1120 ug/g Mn.

The Rotation U plots are receiving small amounts of Mn in both fertilizer and manure. Phosphate fertilizers have been shown to contain anywhere from 10 to 1780 ug/g of Mn (Swaine, 1962). The triple superphosphate used on Rotation U

contained 140 ug Mn/g while the ammonium phosphate (11-48-0) contained 370 Mn/g. Manure also has a variable content: 30 - 540 ug/g of Mn (Swaine, 1962). The relatively high organic matter and clay levels are probably keeping Mn forms balanced in such a way that available soil solution Mn is sufficient for crop growth. No Mn deficiency symptoms have ever been reported on Rotation U, and oats are particularly sensitive to low Mn levels (Sauchelli, 1969). Under the calcareous and well drained conditions of these plots, a Mn toxicity is highly unlikely.

Molybdenum

The Mo content of all the soils samples was below the detection limit of 2 ug/g for neutron activation analysis of Mo. Although values up to 200 ug/g have been reported, the Mo content of soils usually ranges from 0.2 to 5 ug/g, averaging 2 ug/g (Sillanpaa, 1972).

Phosphate fertilizers contain variable amounts of Mo. Values reported by Swaine (1962) are under 35 ug/g, and most are below 10 ug/g. The fertilizer used on Rotation U probably contained very little Mo, although analytical interference prevented a measurement. Manure content of Mo is also variable: 0.5 to 5 g/ton (Sillanpaa, 1972). These sources, plus minute amounts of molybdates dissolved in irrigation water, supply Mo to the rotation U plots.

With the high pH of the Rotation U plots, a deficiency of Mo is improbable. It is far more likely that conditions would permit accumulations of Mo. The results of analysis of

the soils sampled over a 73 year period do not show development of any detectable accumulations of Mo. The amount removed by various mechanisms is balancing the amount added.

Nickel

The soils of Rotation U were below the detection limit of neutron activation analysis which is 50 ug/g Ni. Nickel in the earth's crust is estimated at 75 ug/g. Granite contains 0.5 ug/g, sandstone 2 ug/g, shale 70 ug/g, and limestone 12 ug/g Ni, while soils range from 5 - 500 ug/g (Levinson, 1974). Dudas and Pawluk (1977) reported 5.4 ug/g Ni in a cultivated, well-drained Brown Chernozem. Nickel levels ranging from 21 - 34 ug/g on a winter wheat plot on calcareous silty clay loam, 24-26 ug/g Ni on a grassland plot of acid silty clay loam, and 28-38 ug/g on a barley plot also on calcareous silty clay loam, were reported by Jones et al (1987). The work of McKeague et al (1979) indicated a range of 10 to 28 ug/g Ni in surface soils of the interior plains.

Phosphate fertilizers were reported to contain 7 - 32 ug/g Ni, with triple superphosphate containing approximately 300 ug/g Ni (Swaine, 1962). The 0-43-0 used on Rotation U contained 90 ug/g Ni, and the triple superphosphate 80 ug/g. Manure contains 10 - 12 ug/g Ni (Swaine, 1962). These inputs are so low that Ni toxicity is not a consideration here.

Rubidium

The samples from Rotation U contained 60 - 70 ug/g Rb (Table 43). The fertilizer inputs were insignificant, as

they were at or below the detection limit of 10 ug/g Rb.

The content of Rb in the earth's crust averages 90 ug/g. Granite contains 150 ug/g, sandstone 60 ug/g, shale 140 ug/g, limestone 5 ug/g, and soil 20 - 500 ug/g (Levinson, 1974). In Rothamsted, Rb values in soils under cultivation for 100 years ranged from 70 - 88 ug/g Rb, under different management practices. The researchers concluded that Rb levels showed no consistent changes associated with atmospheric or treatment inputs (Jones et al, 1987).

Scandium

The soils of the Rotation U plots contained 6.7 - 7.2 ug/g Sc (Table 44). The fertilizers contained 3.8 ug/g in the 0-43-0, and 6.8 ug/g in the 11-48-0. The Sc content of the soil shows very little net change with time or with depth.

Selenium

The detection limit for Se by neutron activation analysis is 0.5 ug/g. The Se analysis of Rotation U soils indicate that the Se content of the soil is too low to be detected by neutron activation analysis, lower than 0.5 ug/g. Soils generally contain 0.1 to 2 ug/g Se but high rainfall or irrigation easily leaches soluble Se (Sillanpaa, 1972). The soils of the Canadian plains were found to contain 0.08 to 0.38 ug/g Se, except for one sample which contained 2.2 ug/g Se (McKeague et al, 1979).

Phosphate fertilizer is the only significant source of Se addition to the plots. These fertilizers may contain up

to 4 ug/g Se (Swaine, 1962). The triple superphosphate and ammonium phosphate used on Rotation U both contained less than 1.5 ug/g Se. The low inputs and low soil level of Se virtually eliminate the possibility of Se toxicity from consumption of plants grown on these plots. Selenium deficiency could be a possibility but no symptoms have been reported.

Silver

The Rotation U soils were found to contain less than the detection limit, 2 ug/g Ag. Phosphate fertilizers are reported to contain up to 30 ug/g Ag (Swaine, 1962). The fertilizers used on Rotation U contained 2 ug/g Ag or less. Silver poses no health hazard and it has not been proven to function as a plant nutrient. Silver in the earth's crust averages 0.07 ug/g. The level in granite is 0.04 ug/g, in shale is 0.05 ug/g, in limestone 1 ug/g, and in soil 0.1 ug/g Ag (Plant and Raiswell, 1983).

Strontium

The levels of Sr on the Rotation U plots were always below the detection limit of neutron activation analysis which is 100 ug/g. Levinson (1974) reports Sr content of soil to be 50 - 1000 ug/g. McKeague et al (1979) reports Sr values of 149 to 195 ug/g for interior plains soils. Crops may absorb 0.03 - 4% of soil Sr per year, on soils of higher organic matter content. Sr levels were stable over a cultivation period of over 100 years. On soils of low organic matter the Sr content declined (Jones et al, 1987).

In addition to naturally occurring Sr, additions are made with fertilizer and manure applications and through atmospheric deposition. Strontium occurs naturally in the soil as the stable isotope. Radioactive Sr-90, which is a fission product released mainly by weapons testing, can be deposited on soil from the atmosphere.

The analysis done on Rotation U samples did not distinguish between the isotopes of Sr. As there has been no Sr levels high enough to be detected, the content of these plots is below 100 ug/g, at the low end of the range reported for soil of 50 - 1000 ug/g, as previously mentioned.

Tantalum

The detection limit for Ta is 0.5 ug/g. Both the fertilizers and all the samples were found to contain less than 0.5 ug/g Ta.

Thorium

On the Rotation U plots the total soil content of Th is only 6.1 - 6.7 ug/g (Table 48). This low level has been stable over the 73 years of the plots existence. An average of 10 ug/g Th is found in the earth's crust (Levinson, 1974). Soils often contain values close to the crustal abundance (Bowie and Plant, 1983). The triple superphosphate fertilizer has 3.7 ug/g Th and the ammonium phosphate contains 2.4 ug/g Th. It is not likely that the low input from fertilizer and other sources will cause an accumulation of Th over time.

Titanium

The fertilized and unfertilized halves of Plot 5 show Ti values ranging from 2000 to 2600 ug/g (Table 49). Levinson (1974) quotes a value of 5000 ug/g for soil content of Ti. McKeague et al list values of 0.27 - 0.45% Ti in the surface horizons of soils of the interior plains of Canada. The Ti content of the soils of Rotation U is lower than the values reported in the literature. On Rotation U, 0-43-0 contributed 500 ug/g Ti, and 11-48-0 added 100 ug/g Ti with each application. These are much lower than the 5000 ug/g which is one of the values quoted by Swaine (1962). The other Ti contents of fertilizers reported by Swaine ranged from 43-600 ug/g Ti. These values of Ti in fertilizer are insignificant compared to the soil content.

Tungsten

The Rotation U soils are below the detection limit for W of 1 ug/g. Swaine (1962) reports fertilizers as containing less than 100 ug/g W. The superphosphate and triple superphosphate were found to contain 1 ug/g W. This value is somewhat unreliable as that is the detection limit for W by neutron activation analysis. Deficiencies are not a consideration, as W is not a nutrient. Over 73 years no accumulations have developed.The earth's crust contains 1.5 ug/g W. In granite, levels average 2 ug/g, in sandstone 1.6 ug/g, in shale 2 ug/g, in limestone 0.5 ug/g (Levinson, 1974).

Uranium

Table 50 shows that the U content of the Rotation U plots is low, ranging from 1.8 to 2.3 ug/g. Bowie and Plant (1983) state that locally derived soils tend to mirror the U content of underlying rocks. These researchers report a U range in soil of 1 - 5 ug/g. The U content of phosphate fertilizers, which can reach 100 - 200 ug/g, has been cited as the cause of increased levels of U in areas of intensive agriculture. Swaine (1962) reports values of 50 - 300 ug/g U for rock phosphate. The fertilizers used on Rotation U are high in U, containing 80.7 ug/g in the triple superphosphate and 168 ug/g in the ammonium phosphate. In spite of these U additions, the U level in the soil of the plots remains constant. The lack of any net change in U levels of the plots suggests that contamination by phosphate fertilizer U need not be a concern.

Vanadium

The Rotation U soils maintained a V level of 75 - 82 ug/g V throughout the life of the plot, according to the data of Table 51. This is a similar situation to that at Rothamsted where V levels showed little variation over 100 years of cultivation. Rothamsted soil values ranged from 99 to 140 ug/g under varying treatments (Jones et al, 1987). Soil content of V of 20 to 500 ug/g has been documented (Levinson, 1974). Fertilizer contents of V are reported in the range of 0 - 3900 ug/g V. The 0-43-0 used on Rotation U contained 62 ug/g and the 11-48-0 contained 140 ug/g, well

toward the low end of the reported range.

Zinc

The unfertilized half of Plot 5 contained 94 to 110 ug/g total Zn in the surface 15 cm and 82 to 91 ug/g Zn in the 15 - 30 cm depth (Table 53). The fertilized half contained very similar amounts (86 to 110 ug/g) in the surface soil while the Zn content of the 15 - 30 cm depth was 86 to 99 ug/g. Lindsay (1979) reports Zn content of soils as ranging from 10 - 300 ug/g. The soils of Rotation U fit in this range, but are slightly higher than values of 25 to 75 ug/g Zn reported by McKeague et al (1979) for surface horizons of soils of the Canadian plains.

Zinc is added to the plots in irrigation water, manure, and fertilizer, and through accretion of soil. Farmyard manure has been reported to contain 10 - 200 ug Zn/g dry matter (Swaine, 1962). The analysis of the fertilizer used on Rotation U indicated 64 ug/g Zn in the triple superphosphate and 70 ug/g Zn in the ammonium phosphate. Zinc is removed from the plots by erosion, leaching, and plant uptake. Analysis of Rotation U soils shows neither accumulations nor depletions of total soil Zn. No toxicities of Zn are likely to occur at this pH level, and no deficiency symptoms have ever been recorded.

CONCLUSIONS

Tillage and cropping lowers soil structural stability. This tendency can be offset to a great degree by minimizing tillage, by organic matter additions, and by growth of grass and/or legume crops. The crop rotation system and amendment schedule of the Rotation U plots is likely responsible for the minimal deterioration of the soil structure over the past three-quarters of a century, even though no attempt was made to minimize tillage throughout the plot's lifetime.

There appears to be a trend toward increase in clay content with longterm cultivation, suggesting a degree of structural deterioration. The data of the later decades show less change in clay content, an indication that the soil is becoming less erodible possibly as a result of the cementing effects of $CaCO_3$, the adhesive effects of decomposing organic matter, and erosion protection techniques practiced on Rotation U.

Cation exchange capacity, organic matter content, total N, P, and S are being maintained at fairly stable levels. There is no indication of a decline in any of these parameters, as is often reported by researchers.

The levels of K are declining as the plot system continues to operate under a K deficiency. At some time in the future, K fertilizer applications may be required. At present, there is adequate exchangeable K for crop needs.

The Ca content of the soil of the Rotation U plots has increased markedly. The rate of increase, however, is

declining. It is unlikely that the Ca concentrations will increase very much in the future, rather the present level will be maintained. The increase in Ca concentration may be considered beneficial to the soil, as $CaCO_3$ acts as a cementing agent and assists in maintaining soil aggregate stability.

Applications of manure and commercial N and P fertilizer are necessary to maintain yield and avoid nutrient depletion. The quantities used are minimal and no evidence of accumulation of these elements is supplied by these treatments. The micronutrient elements Zn, Cu, Fe, Mn, and B are less available at high pH but there is no indication of depletion of soil reserves of these elements and no symptoms of deficiency shown by the crops grown on Rotation U. Trace elements in manure, irrigation water, and as contaminants of fertilizer are likely balancing plant uptake.

On Rotation U, the alfalfa crops are an extremely important part of the cropping sequence. Their contribution to organic matter level maintenance is a major factor in limiting the degradation of the soil structure.

With proper management techniques, including minimal tillage, appropriate manure and commercial fertilizer amendments, crop rotations including legumes, limiting or eliminating fallow, it is possible to maintain and even improve soil productivity while retaining nutrient status and minimizing structure degradation.

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APPENDIX

Table 16. Content of total nitrogen, phosphorus and sulphur (%) in Rotation U plot 5 from 1911 to 1984.

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Total N (%)										
Unfertilized	0-15	0.19	0.17	0.21	0.22	0.19	0.21	0.15	0.19	0.20
	15-30	0.13	0.13	0.19	0.18	0.20	0.18	0.14	0.18	0.17
Fertilized	0-15			0.21	0.21	0.22	0.21	0.21	0.20	0.18
	15-30			0.19	0.16	0.17	0.17	0.19	0.17	0.17
Total P (%)										
Unfertilized	0-15	.042	.046	.049	.050	.050	.048	.038	.050	.053
	15-30	.045	.041	.052	.047	.046	.049	.040	.054	.052
Fertilized	0-15			.048	.049	.052	.054	.042	.054	.053
	15-30			.050	.046	.049	.049	.054	.051	.054
Total S (%)										
Unfertilized	0-15	.063	.057	.051	.060	.084	.069	.066	.054	.069
	15-30	.051	.051	.054	.054	.084	.126	.066	.057	.054
Fertilized	0-15			.051	.054	.090	.066	.060	.075	.054
	15-30			.054	.048	.090	.156	.090	.054	.051

Table 17. Cation exchange capacity (cmol/kg) of soil of Rotation U plot 5 from 1911 to 1984.

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0-15	20.1	19.5	24.1	23.3	24.2	24.0	23.7	22.8	25.2
	15-30	20.7	19.1	20.1	22.8	23.8	23.7	22.4	22.7	24.6
	30-60						16.8	19.8	20.6	
	60-90						19.6	16.3	15.7	
Fertilized	0-15			21.8	22.0	22.5	24.4	19.9	20.8	21.2
	15-30			22.5	19.1	22.4	22.7	22.2	22.1	22.2
	30-60						19.9	18.7	14.5	
	60-90						16.6	16.6	17.5	

Table 18. Content of total K (ug/g) of soil of Rotation U plot 5 from 1911 to 1984.

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0-15	12910	14204	14091	15754	14466	15212	14303	9542	9568
	15-30	10984	10951	12306	11510	13150	14431	13026	8984	6421
Fertilized	0-15			14863	10135	10875	13458	10134	10240	10799
	15-30			13571	7909	10438	13936	13233	9282	8450

Table 19. Content of CaCO3(%) of soil of Rotation U plot 5 from 1911 to 1984.

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Unfertilized	0-15	0.3	0.3	1.3	1.1	1.3	2.8	3.2	3.6	4.0
	15-30	1.6	0.2	5.6	1.9	5.4	4.8	4.8	4.9	5.6
	30-60						20.0	16.9	18.8	
	60-90						14.7	17.6	17.4	
Fertilized	0-15			1.4	0.5	1.2	2.0	3.6	2.5	4.0
	15-30			3.6	0.4	2.2	3.6	6.2	5.2	5.4
	30-60						15.0	17.5	18.2	
	60-90						16.0	18.4	16.0	

Table 20. Content of total carbon (%) of soil of Rotation U plot 5 from 1911 to 1984.

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Unfertilized	0-15	1.95	1.47	2.15	2.64	2.50	2.44	2.56	2.38	2.68
	15-30	1.54	1.15	2.51	2.12	2.50	2.43	2.25	2.22	2.52
	30-60						3.21	3.11	3.16	
	60-90						2.32	2.68	2.71	
Fertilized	0-15			1.99	2.16	2.12	2.33	2.49	2.52	2.68
	15-30			2.23	1.66	1.99	2.13	2.39	2.25	2.56
	30-60						2.68	2.99	3.13	
	60-90						2.44	2.82	2.62	

Table 21. Content of total Ca (%) of soil of Rotation U plot 5 from 1911 to 1984.

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	0.6	0.4	1.1	0.8	1.4	1.5	1.4	1.6	1.9
	15- 30	0.9	0.4	2.1	1.2	2.3	1.6	1.9	2.0	2.3
	30- 60						6.8	5.6	6.1	
	60- 90						5.0	5.9	6.3	
	90-120								5.1	
	120-150								3.7	
	150-180								2.5	
Fertilized	0- 15			0.9	0.7	0.8	2.2	1.6	1.4	1.6
	15- 30			1.6	0.6	1.1	1.3	2.5	2.0	2.1
	30- 60						5.3	5.9	5.9	
	60- 90						5.3	5.7	5.6	
	90-120								5.1	
	120-150								4.4	
	150-180								3.5	

Table 22. Particle size distribution by complete dispersion and gravity sedimentation of soils of Rotation U plot 5 from 1911 to 1984.

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
% Clay										
Unfertilized	0-15	10.8	13.2	22.6	19.6		26.1	24.8	25.8	28.3
	15-30	16.5	10.6	19.8	20.9	27.1	24.5	28.4	25.1	26.1
Fertilized	0-15			18.6	19.2	26.2	23.6	25.8	25.3	26.0
	15-30			20.6	20.2	22.6	24.5	26.9	28.1	26.7
% Silt										
Unfertilized	0-15	34.8	36.5	33.0	35.8		31.3	32.0	32.1	26.1
	15-30	28.6	38.8	34.9	32.1	28.2	28.8	26.3	28.9	29.8
Fertilized	0-15			31.6	33.4	28.0	32.3	29.2	32.2	32.0
	15-30			29.9	33.6	29.4	28.1	28.3	28.0	26.1
% Sand										
Unfertilized	0-15	54.5	50.3	46.4	44.6		42.6	43.2	42.1	45.6
	15-30	54.9	50.6	45.3	47.0	44.7	46.7	45.3	46.0	44.1
Fertilized	0-15			49.8	47.4	45.8	44.1	45.0	42.5	42.0
	15-30			49.5	46.2	48.0	47.4	44.8	43.9	47.2

Table 23. Content of water-dispersible clay as an indication of aggregate stability of soils of Rotation U plot 5 from 1911 to 1984.

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
% Clay										
Unfertilized	0-15	1.6	1.2	2.9	2.5		7.4	6.0	4.5	4.4
	15-30	1.7	1.9	3.0	3.6	5.9	6.8	5.9	2.6	3.5
Fertilized	0-15			2.2	2.5	6.4	7.0	4.0	2.8	2.6
	15-30			2.8	2.5	7.3	7.7	9.0	6.5	3.8

Table 24. Content of Aluminum (%) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.01%).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	4.96	4.93	4.97	5.06	5.14	4.97	4.44	4.83	4.84
	15- 30	4.89	5.04	4.77	5.05	4.25	4.49	4.86	4.86	4.80
	30- 60						3.65	4.20	4.14	
	60- 90						4.56	4.15	3.98	
	90-120								4.25	
	120-150								4.23	
	150-180								4.79	
Fertilized	0- 15			4.82	5.05	4.92	4.86	5.01	5.00	4.93
	15- 30			4.57	4.57	4.95	4.68	4.40	4.84	4.76
	30- 60						4.48	4.17	4.10	
	60- 90						4.26	4.04	4.12	
	90-120								4.03	
	120-150								4.27	
	150-180								4.49	

Table 25. Content of Antimony (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.1 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	0.9	0.9	1.0	0.9	1.0	0.9	0.9	0.9	0.9
	15- 30	0.9	1.0	0.9	0.9	0.9	1.0	0.9	0.9	1.0
	30- 60						0.8	0.8	0.9	
	60- 90						0.8	0.9	0.8	
	90-120								0.9	
	120-150								0.8	
	150-180								0.8	
Fertilized	0- 15			0.9	0.9	1.0	0.9	0.9	0.9	1.0
	15- 30			0.9	0.9	0.9	0.9	1.0	1.0	0.9
	30- 60						0.9	0.9	0.8	
	60- 90						0.9	0.9	0.9	
	90-120								0.9	
	120-150								0.8	
	150-180								0.8	

Table 26. Content of Arsenic (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 1 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	8	8	9	9	8	9	8	8	9
	15- 30	8	9	9	8	8	8	8	7	8
	30- 60						6	7	7	
	60- 90						7	7	6	
	90-120								7	
	120-150								7	
	150-180								7	
Fertilized	0-15			8	8	8	8	8	8	9
	15-30			8	8	8	8	9	8	8
	30-60						7	7	7	
	60-90						7	6	6	
	90-120								7	
	120-150								6	
	150-180								7	

Table 27. Content of Barium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 20 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	640	630	630	590	590	640	590	610	630
	15- 30	580	620	610	620	610	610	590	580	600
	30- 60						650	590	610	
	60- 90						720	660	670	
	90-120								680	
	120-150								680	
	150-180								710	
Fertilized	0- 15			620	590	610	640	610	590	640
	15- 30			620	630	620	590	610	610	600
	30- 60						660	600	700	
	60- 90						630	680	670	
	90-120								630	
	120-150								680	
	150-180								690	

Table 28. Content of Boron (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.5 ug/g).

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Unfertilized	0- 15	44	39	37	42	44	43	38	44	39
	15- 30	40	39	41	44	38	39	43	38	37
	30- 60						34	34	33	
	60- 90						34	32	33	
	90-120								34	
	120-150								41	
	150-180								40	
Fertilized	0- 15			40	36	38	38	36	40	40
	15- 30			38	41	40	39	39	38	40
	30- 60						35	32	36	
	60- 90						37	30	37	
	90-120								34	
	120-150								37	
	150-180								37	

Table 29. Content of Bromine (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.5 ug/g).

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Unfertilized	0- 15	2.4	2.3	2.5	2.5	3.0	2.8	2.7	2.7	2.9
	15- 30	2.5	2.6	3.0	2.7	2.9	2.9	3.0	2.8	3.1
	30- 60						3.4	3.9	4.2	
	60- 90						3.7	3.8	3.2	
	90-120								2.9	
	120-150								2.2	
	150-180								1.7	
Fertilized	0- 15			2.3	2.4	2.9	3.1	3.1	2.8	3.3
	15- 30			2.4	2.2	2.9	2.7	3.2	3.3	3.3
	30- 60						4.0	3.8	3.9	
	60- 90						3.4	3.2	3.5	
	90-120								3.1	
	120-150								2.1	
	150-180								1.6	

Table 30. Content of Cerium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 1 ug/g).

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Unfertilized	0- 15	45	43	45	42	42	44	44	43	43
	15- 30	42	46	43	45	42	42	42	42	42
	30- 60						37	38	37	
	60- 90						41	38	38	
	90-120								39	
	120-150								40	
	150-180								47	
Fertilized	0- 15			44	43	44	42	44	42	44
	15- 30			42	45	45	44	42	45	43
	30- 60						42	39	38	
	60- 90						38	36	39	
	90-120								39	
	120-150								40	
	150-180								44	

Table 31. Content of Cesium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.2 ug/g).

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Unfertilized	0- 15	3.1	3.2	2.9	3.4	2.9	3.0	3.3	3.1	2.9
	15- 30	3.0	2.9	2.9	3.4	2.9	3.1	3.3	3.3	2.8
	30- 60						3.1	3.1	2.6	
	60- 90						3.5	3.2	2.8	
	90-120								2.6	
	120-150								2.8	
	150-180								3.5	
Fertilized	0- 15			3.1	2.9	3.3	3.0	3.4	3.3	3.3
	15- 30			3.0	2.9	2.9	3.2	2.9	3.2	3.3
	30- 60						2.9	3.3	3.0	
	60- 90						3.0	2.9	2.9	
	90-120								3.2	
	120-150								2.9	
	150-180								2.9	

Table 32. Content of Chlorine (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 20 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	80	80	<50	80	<80	<50	<50	<50	110
	15- 30	<50	180	<50	70	60	<50	<50	<50	<50
	30- 60						70	<50	<50	
	60- 90						70	80	<50	
	90-120								<50	
	120-150								80	
	150-180								70	
Fertilized	0- 15			<50	80	70	80	70	<50	<50
	15- 30			<50	<50	<50	<50	<50	<50	80
	30- 60						<50	<50	<50	
	60- 90						<50	<50	<50	
	90-120								<50	
	120-150								<50	
	150-180								100	

Table 33. Content of Chromium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.5 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	49	47	47	45	48	53	47	51	48
	15- 30	48	51	49	52	47	50	49	48	47
	30- 60						41	44	41	
	60- 90						46	44	42	
	90-120								44	
	120-150								47	
	150-180								50	
Fertilized	0- 15			49	47	49	49	48	49	48
	15- 30			44	51	49	50	49	50	45
	30- 60						45	46	43	
	60- 90						44	41	45	
	90-120								45	
	120-150								45	
	150-180								48	

Table 34. Content of Cobalt (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.1 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	6.8	6.6	6.5	6.6	6.3	6.9	6.4	6.4	6.6
	15- 30	6.8	6.8	6.5	6.9	6.3	6.4	6.8	6.3	6.7
	30- 60						5.5	6.3	5.9	
	60- 90						6.8	5.9	5.6	
	90-120								6.0	
	120-150								6.5	
	150-180								7.3	
Fertilized	0- 15			6.0	5.9	6.6	6.5	6.6	6.6	6.9
	15- 30			6.0	6.5	6.7	6.4	6.3	6.7	6.9
	30- 60						6.7	6.3	6.1	
	60- 90						6.0	5.9	5.9	
	90-120								6.2	
	120-150								6.2	
	150-180								7.1	

Table 35. Content of Dysprosium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.5 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	4.4	3.8	4.0	4.4	4.5	4.2	3.9	4.0	4.1
	15- 30	4.1	4.1	3.9	4.4	3.3	3.4	4.5	3.9	4.2
	30- 60						3.2	3.7	3.7	
	60- 90						3.8	3.9	3.2	
	90-120								3.7	
	120-150								3.8	
	150-180								4.1	
Fertilized	0- 15			3.8	4.3	4.4	4.1	4.3	3.9	4.1
	15- 30			4.0	3.6	4.1	3.8	3.7	4.6	4.6
	30- 60						3.9	3.8	3.6	
	60- 90						3.7	3.6	3.4	
	90-120								3.8	
	120-150								3.5	
	150-180								4.0	

Table 36. Content of Europium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.05 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	0.59	0.75	0.72	0.75	0.77	0.82	0.73	0.73	0.76
	15- 30	0.71	0.76	0.70	0.77	0.64	0.75	0.73	0.71	0.79
	30- 60						0.67	0.66	0.65	
	60- 90						0.65	0.70	0.70	
	90-120								0.64	
	120-150								0.73	
	150-180								0.82	
Fertilized	0- 15			0.69	0.74	0.73	0.74	0.83	0.72	0.73
	15- 30			0.69	0.73	0.74	0.81	0.75	0.75	0.73
	30- 60						0.70	0.66	0.65	
	60- 90						0.67	0.64	0.71	
	90-120								0.70	
	120-150								0.73	
	150-180								0.83	

Table 37. Content of Hafnium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.2 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	5.8	6.3	5.8	6.0	5.8	6.0	5.4	5.6	5.6
	15- 30	5.5	6.2	5.8	5.8	5.5	5.8	5.6	5.6	5.4
	30- 60						4.5	4.8	4.4	
	60- 90						4.1	4.6	4.6	
	90-120								4.3	
	120-150								4.6	
	150-180								4.7	
Fertilized	0- 15			6.3	5.9	5.7	5.5	5.8	5.7	5.6
	15- 30			5.8	5.8	6.2	6.1	5.3	5.7	5.4
	30- 60						5.1	4.8	4.4	
	60- 90						4.6	4.4	4.5	
	90-120								4.8	
	120-150								4.9	
	150-180								4.8	

Table 38. Content of Iron (%) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.005 %).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	1.98	1.83	1.89	1.88	1.80	1.93	1.83	1.85	1.90
	15- 30	1.79	1.88	1.82	1.90	1.79	1.84	1.86	1.81	1.81
	30- 60						1.59	1.69	1.58	
	60- 90						1.83	1.65	1.57	
	90-120								1.69	
	120-150								1.82	
	150-180								2.06	
Fertilized	0- 15			1.82	1.76	1.84	1.81	1.89	1.87	1.93
	15- 30			1.72	1.88	1.91	1.85	1.82	1.90	1.82
	30- 60						1.75	1.69	1.60	
	60- 90						1.65	1.58	1.65	
	90-120								1.70	
	120-150								1.79	
	150-180								1.93	

Table 39. Content of Lanthanum (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.1 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	24.2	23.5	24.4	24.3	22.9	24.7	24.4	24.4	24.1
	15- 30	23.0	25.2	23.5	24.7	23.1	23.7	23.7	24.0	23.6
	30- 60						20.7	21.4	20.9	
	60- 90						22.9	21.0	20.5	
	90-120								21.4	
	120-150								22.5	
	150-180								25.7	
Fertilized	0- 15			24.1	23.7	23.9	23.4	24.3	23.9	24.3
	15- 30			23.2	24.3	24.4	24.1	23.3	25.1	23.5
	30- 60						23.2	22.0	21.1	
	60- 90						21.4	20.0	22.3	
	90-120								21.9	
	120-150								22.6	
	150-180								24.0	

Table 40. Content of Lutetium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.01 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	0.29	0.30	0.29	0.31	0.30	0.32	0.30	0.30	0.30
	15- 30	0.28	0.31	0.29	0.31	0.30	0.30	0.30	0.29	0.29
	30- 60						0.26	0.27	0.26	
	60- 90						0.25	0.24	0.24	
	90-120								0.26	
	120-150								0.27	
	150-180								0.28	
Fertilized	0- 15			0.30	0.29	0.29	0.30	0.30	0.30	0.31
	15- 30			0.29	0.31	0.32	0.30	0.29	0.29	0.30
	30- 60						0.29	0.26	0.26	
	60- 90						0.26	0.24	0.26	
	90-120								0.26	
	120-150								0.28	
	150-180								0.31	

Table 41. Content of Manganese (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.1 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	370	400	380	390	380	370	330	370	370
	15- 30	330	350	350	370	330	340	380	360	360
	30- 60						250	310	320	
	60- 90						350	290	280	
	90-120								300	
	120-150								370	
	150-180								410	
Fertilized	0- 15			380	380	380	360	390	380	380
	15- 30			360	340	350	360	330	370	360
	30- 60						360	320	320	
	60- 90						310	290	340	
	90-120								300	
	120-150								350	
	150-180								360	

Table 42. Content of Neodymium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 3 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	19	20	18	18	17	18	17	17	17
	15- 30	16	19	18	18	18	18	17	17	16
	30- 60						15	15	15	
	60- 90						17	15	16	
	90-120								15	
	120-150								16	
	150-180								19	
Fertilized	0- 15			20	16	17	16	18	17	18
	15- 30			18	20	18	18	17	17	17
	30- 60						17	16	17	
	60- 90						15	15	16	
	90-120								16	
	120-150								17	
	150-180								18	

Table 43. Content of Rubidium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 10 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	70	60	70	70	70	70	70	70	70
	15- 30	60	70	60	70	70	60	70	60	70
	30- 60						60	60	50	
	60- 90						60	60	60	
	90-120								60	
	120-150								60	
	150-180								70	
Fertilized	0- 15			70	60	70	70	70	70	60
	15- 30			70	70	70	70		70	60
	30- 60						60	60	50	
	60- 90						60	50	60	
	90-120								60	
	120-150								60	
	150-180								70	

Table 44. Content of Scandium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.01 ug/g).

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Unfertilized	0- 15	7.2	6.9	7.1	6.9	6.7	7.2	6.9	7.0	7.1
	15- 30	6.7	7.0	6.8	7.1	6.7	6.8	7.0	6.8	6.8
	30- 60						6.0	6.4	6.0	
	60- 90						7.0	6.2	5.9	
	90-120								6.2	
	120-150								7.0	
	150-180								7.8	
Fertilized	0- 15			6.7	6.7	6.9	6.8	7.1	7.1	7.2
	15- 30			6.6	7.0	7.1	7.0	6.8	7.1	6.8
	30- 60						6.6	6.4	6.1	
	60- 90						6.2	6.0	6.2	
	90-120								6.4	
	120-150								6.7	
	150-180								7.3	

Table 45. Content of Samarium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.01 ug/g).

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Unfertilized	0- 15	3.77	3.68	3.74	3.70	3.54	3.71	3.83	3.65	3.63
	15- 30	3.62	3.92	3.64	3.81	3.56	3.60	3.61	3.51	3.45
	30- 60						3.10	3.23	3.15	
	60- 90						3.36	3.16	3.14	
	90-120								3.20	
	120-150								3.37	
	150-180								3.81	
Fertilized	0- 15			3.67	3.64	3.71	3.59	3.68	3.59	3.67
	15- 30			3.50	3.71	3.73	3.69	3.57	3.72	3.54
	30- 60						3.49	3.33	3.18	
	60- 90						3.22	3.03	3.22	
	90-120								3.28	
	120-150								3.42	
	150-180								3.63	

Table 46. Content of Sodium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 30 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	5800	5900	5700	5600	5500	5700	5400	5600	5600
	15- 30	5400	5800	5300	5600	5300	5700	5400	5400	5400
	30- 60						4600	4800	4500	
	60- 90						5900	5000	4800	
	90-120								5100	
	120-150								5600	
	150-180								6700	
Fertilized	0- 15			5700	5700	5700	5500	5600	5500	5600
	15- 30			5400	5900	5700	5900	5400	5600	5400
	30- 60						5100	4900	4600	
	60- 90						5000	4700	4900	
	90-120								5200	
	120-150								5900	
	150-180								6500	

Table 47 Content of Terbium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.1 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	0.5	0.4	0.5	0.5	0.5	0.4	0.4	0.5	0.5
	15- 30	0.5	0.5	0.4	0.6	0.4	0.5	0.5	0.4	0.5
	30- 60						0.4	0.5	0.5	
	60- 90						0.4	0.4	0.4	
	90-120								0.4	
	120-150								0.5	
	150-180								0.5	
Fertilized	0- 15			0.5	0.5	0.5	0.5	0.4	0.5	0.5
	15- 30			0.5	0.4	0.5	0.4	0.5	0.5	0.4
	30- 60						0.4	0.4	0.4	
	60- 90						0.4	0.3	0.4	
	90-120								0.5	
	120-150								0.4	
	150-180								0.5	

Table 48. Content of Thorium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.2 ug/g).

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Unfertilized	0- 15	6.4	6.1	6.4	6.2	6.2	6.7	6.6	6.3	6.4
	15- 30	6.0	6.6	6.1	6.8	6.0	6.3	6.1	6.1	6.0
	30- 60						5.4	5.7	5.4	
	60- 90						6.0	5.3	5.3	
	90-120								5.6	
	120-150								5.9	
	150-180								6.9	
Fertilized	0- 15			6.2	6.2	6.4	6.0	6.4	6.1	6.4
	15- 30			6.1	6.5	6.4	6.6	6.0	6.6	6.3
	30- 60						6.1	5.7	5.5	
	60- 90						5.5	5.0	5.6	
	90-120								5.6	
	120-150								5.7	
	150-180								6.4	

Table 49. Content of Titanium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 100 ug/g).

		1911	1922	1933	1941	1951	1961	1971	1981	1984
	Depth (cm)									
Unfertilized	0- 15	2200	2300	2200	2400	2600	2400	2100	2200	2200
	15- 30	2100	2200	2200	2400	1900	2200	2400	2300	2300
	30- 60						1700	2000	1900	
	60- 90						2100	1800	1700	
	90-120								1900	
	120-150								2100	
	150-180								2200	
Fertilized	0- 15			2400	2300	2300	2100	2500	2500	2200
	15- 30			2200	2300	2200	2100	2000	2300	2200
	30- 60						2200	1900	2000	
	60- 90						1800	1900	1900	
	90-120								2000	
	120-150								2000	
	150-180								2200	

Table 50. Content of Uranium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.1 ug/g).

	1911	1922	1933	1941	1951	1961	1971	1981	1984
Depth (cm)									
Unfertilized 0- 15	2.1	2.3	2.3	2.3	2.1	2.1	2.0	1.9	2.0
15- 30	2.1	2.0	2.1	2.2	2.1	1.9	2.0	2.0	2.1
30- 60						1.8	1.9	1.9	
60- 90						1.8	1.9	1.9	
90-120								2.0	
120-150								1.9	
150-180								2.2	
Fertilized 0- 15			2.1	2.2	2.3	1.8	2.1	2.2	2.1
15- 30			2.2	2.1	2.3	2.1	2.0	2.0	1.9
30- 60						1.9	1.9	1.8	
60- 90						1.8	1.9	2.0	
90-120								2.2	
120-150								2.0	
150-180								2.1	

Table 51. Content of Vanadium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 1 ug/g).

	1911	1922	1933	1941	1951	1961	1971	1981	1984
Depth (cm)									
Unfertilized 0- 15	76	75	76	78	81	77	70	75	77
15- 30	77	79	81	80	68	67	78	79	78
30- 60						63	71	70	
60- 90						74	69	62	
90-120								73	
120-150								72	
150-180								73	
Fertilized 0- 15			75	78	77	75	82	78	78
15- 30			72	71	79	73	70	76	75
30- 60						75	72	71	
60- 90						69	69	68	
90-120								63	
120-150								310	
150-180								320	

Table 52. Content of Ytterbium (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 0.05 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	1.81	1.80	1.92	1.95	1.83	1.92	1.86	1.86	1.93
	15- 30	1.73	2.01	1.81	1.87	1.77	1.85	1.83	1.78	1.82
	30- 60						1.53	1.61	1.57	
	60- 90						1.60	1.60	1.56	
	90-120								1.53	
	120-150								1.59	
	150-180								1.90	
Fertilized	0- 15			1.90	1.83	1.88	1.81	1.89	1.84	1.91
	15- 30			1.73	1.88	1.93	1.94	1.80	1.92	1.81
	30- 60						1.65	1.69	1.51	
	60- 90						1.62	1.54	1.70	
	90-120								1.67	
	120-150								1.76	
	150-180								1.81	

Table 53. Content of Zinc (ug/g) of soils of Rotation U plot 5 from 1911 to 1984 (detection limit = 5 ug/g).

	Depth (cm)	1911	1922	1933	1941	1951	1961	1971	1981	1984
Unfertilized	0- 15	110	90	100	96	94	90	95	99	90
	15- 30	86	88	82	90	95	85	89	91	79
	30- 60						81	81	82	
	60- 90						78	78	75	
	90-120								84	
	120-150								93	
	150-180								93	
Fertilized	0- 15			95	93	110	86	87	90	94
	15- 30			90	88	86	93	88	92	99
	30- 60						89	91	87	
	60- 90						85	88	80	
	90-120								87	
	120-150								85	
	150-180								97	